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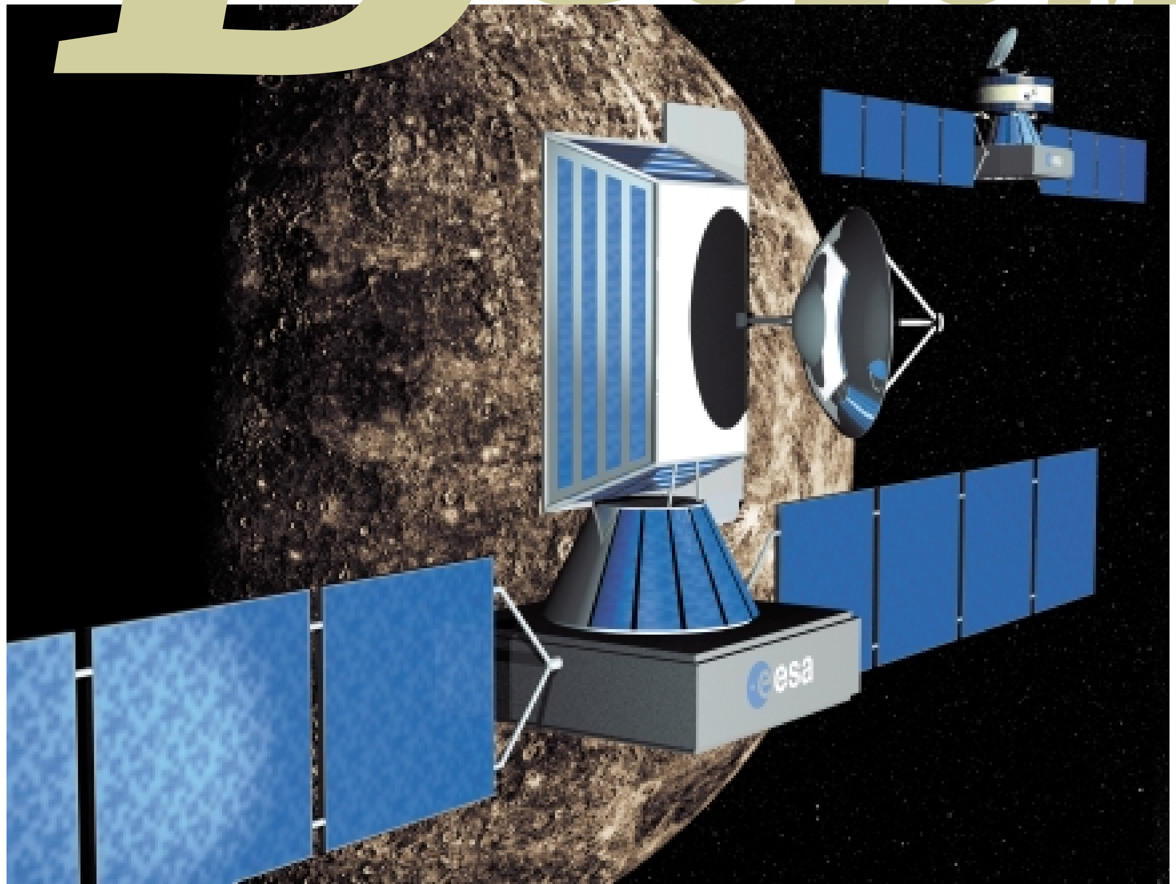
BEPI-COLOMBO



Interdisciplinary Mission to Planet Mercury

European Space Agency
Agence spatiale européenne

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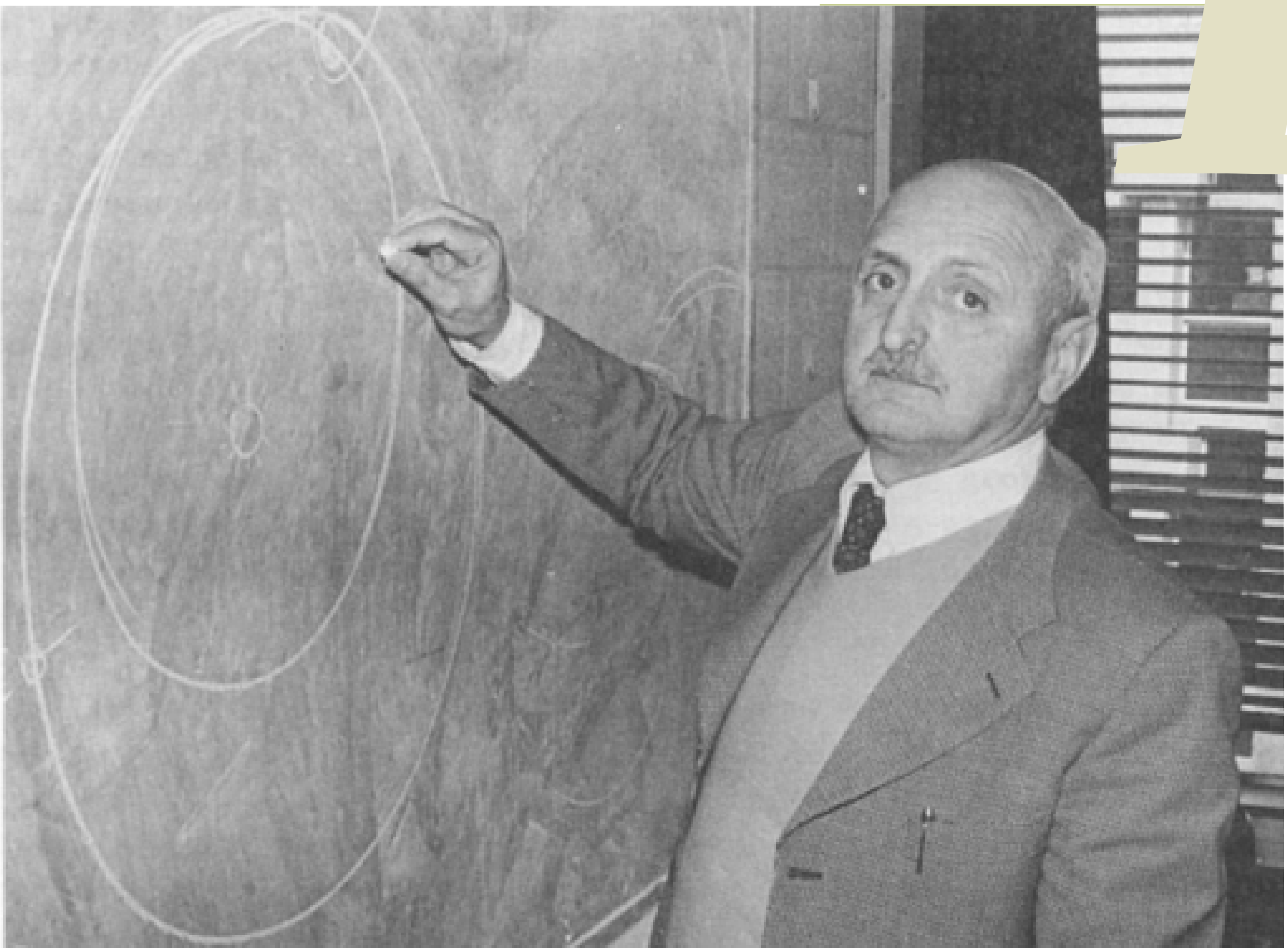

Giuseppe Colombo (1920-1984)

ESA's Science Programme Committee recognized the achievements of the late Giuseppe (Bepi) Colombo of the University of Padua by adopting his name for the Mercury Cornerstone. Giuseppe Colombo was a mathematician and engineer of astonishing imagination. The Italian scientist explained, as an unsuspected resonance, Mercury's peculiar habit of rotating three times around itself in every two revolutions around the Sun. He also suggested to NASA how to place Mariner 10 into an orbit that would enable the spacecraft to perform three flybys of the planet Mercury in 1974-1975.

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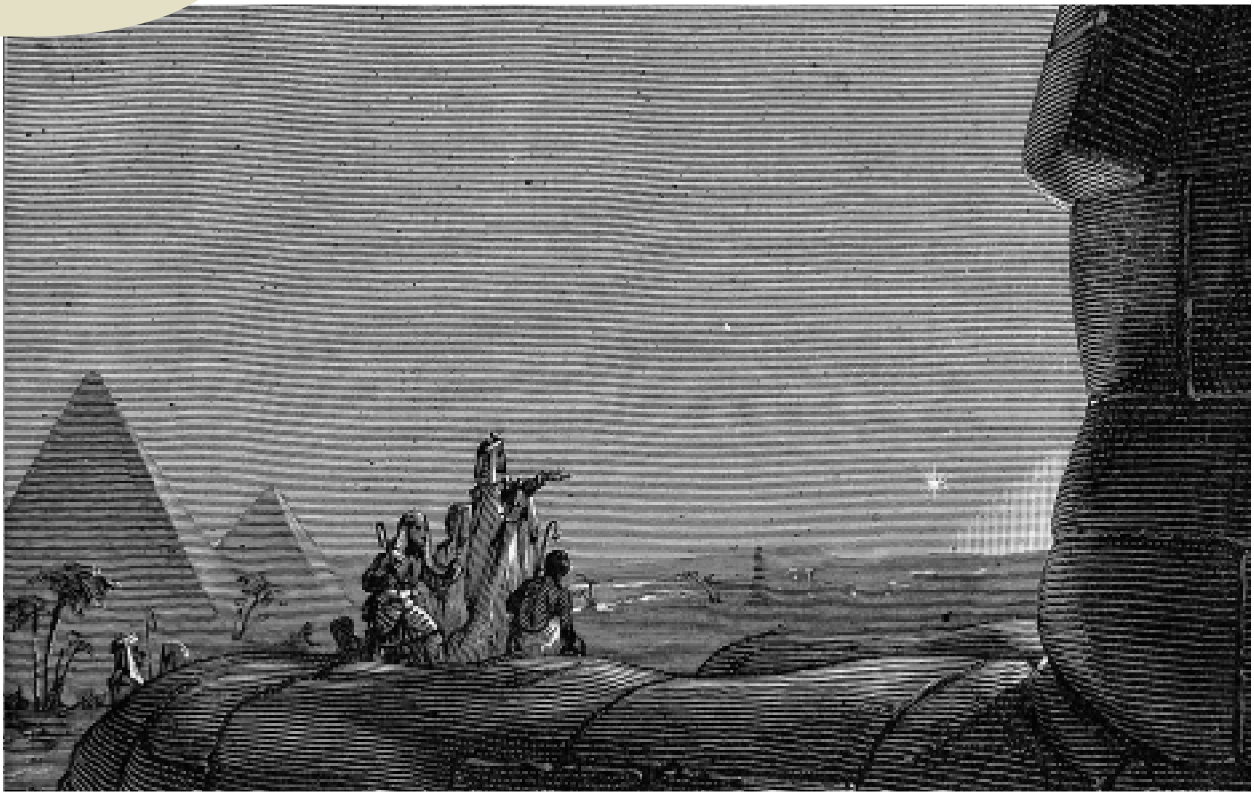


Figure 1: Mercury was already known in ancient Egypt (after an engraving of Régnier Barbant in G. Flammarion, Astronomie Populaire, 1881).

Although the planet Mercury was known to the ancient Egyptians (Figure 1) it is still largely unexplored. Its proximity to the Sun makes it hard to see. From the Earth, Mercury is, at best, visible for just two hours before sunrise or after sunset, when the sky is not very dark. Telescopes in orbit, such as the Hubble Space Telescope, usually cannot target Mercury because of the risk of solar rays damaging the instruments.

Nor is inserting a spacecraft into orbit around Mercury a trivial task. It has never been done. One problem is the large change in the gravitational potential of the Sun in going from the orbit of the Earth to the orbit of Mercury. The direct radiation from the Sun is also ten times more intense, and over the sunlit hemisphere of Mercury the heat flux is further increased by reflected sunlight and infrared emission. The thermal burden on any orbiter is enormous.

The American probe Mariner 10 made three flybys of Mercury in 1974-1975. It obtained images of somewhat less than half its surface (Figure 2) and discovered its unexpected magnetic field. After a quarter of a century, the Mariner 10 results have been fully exploited by scientists but the most important questions remain unanswered.

With a radius of 2440 km Mercury is slightly larger than our Moon. It revolves around the Sun in almost 88 days and rotates around its axis in 2/3 of that time. Its orbit is very eccentric and its distance from the Sun varies between 0.308 and 0.466 AU.

As the nearest planet to the Sun, Mercury plays an important role in constraining and testing all theories of how planets form. In particular, Mercury, Venus, Earth and Mars make up the family of terrestrial planets (Figure 3), each member of which carries information that is essential for retracing the history of the whole group. Knowledge about the origin and evolution of these planets is one of the keys to understanding how conditions that support life have arisen in the Solar System, and possibly elsewhere. As long as Earth-like planets orbiting other stars remain inaccessible to astronomers, the Solar System is the only laboratory where we can test models applicable to other planetary systems. The exploration of Mercury is therefore of fundamental importance for answering questions of astrophysical and philosophical significance, such as: "Are Earth-like planets common in the Galaxy?"

Space missions to the giant planets and to comets and asteroids provide information on the cold regions of the Solar System. With the Rosetta mission to Comet P/Wirtanen, to be launched in 2003 as Cornerstone 3, the European Space Agency will investigate some of the pristine material originating in the outer regions of the cloud of gas and dust that surrounded the newborn Sun. Mercury represents the opposite challenge, since this small and important body will yield complementary data about planetary formation in the hottest part of that solar nebula. Consequently, the BepiColombo mission to Mercury, selected as Cornerstone-5 on 12 October 2000, appears to be the logical next step in ESA's planetary exploration programme.

BepiColombo
Mercury Cornerstone - Mission Summary

Scientific Objectives	• Origin and evolution of a planet close to the parent star • Mercury as a planet: form, interior structure, geology, composition and craters • Origin of Mercury’s magnetic field • Mercury’s vestigial atmosphere (exosphere): composition and dynamics • Mercury's magnetized envelope (magnetosphere): structure and dynamics • Test of Einstein’s theory of general relativity • Detection of potentially Earth-threatening asteroids
Three payloads	**Mercury Planetary Orbiter (MPO):** imagers, spectrometers (IR, UV, X-ray, γ-ray, neutron), Ka-band transponder, accelerometer, altimeter, and asteroidal telescope **Mercury Magnetospheric Orbiter (MMO):** magnetometer, ion spectrometer, electron energy analyser, cold and energetic plasma detectors, plasma wave analyser, and imager **Mercury Surface Element (MSE):** thermal and physical properties analyser, alpha X-ray spectrometers, seismometer, magnetometer, and imagers
Transfer to Mercury	• Two launches: MPO and MMO-MSE composite • Interplanetary cruise with Solar Electric Propulsion Module and gravity assists of the Moon, Venus and Mercury; Solar Electric Propulsion Module to be jettisoned upon arrival at Mercury • Mercury capture, MPO and MMO insertion in polar orbits, and MSE descent with Chemical Propulsion Module; MSE soft landing with airbags

Spacecraft modules	**MPO**	**MMO**	**MSE**
Stabilisation	3-axis	15 rpm spin	NA
Orientation	Nadir pointing	Spin axis at 90° to Sun	NA
Mass	357 kg	165 kg	44 kg
Power or energy	420 W	185 W	1.7 kWh
TM band	X/Ka	X	UHF
Antenna	1.5 m diameter	1 m diameter, despun	Cross dipole
Deployment	400 x 1500 km altitude	400 x 12 000 km altitude	± 85° latitude
Operational lifetime	> 1 year	> 1 year	> 1 week
Data volume	1550 Gb/year	160 Gb/year	75/138 Mb/week*
Equivalent average bit rate	50 kb/s	5 kb/s	128/228 b/s*

Propulsion modules	**Solar Electric Propulsion Module**	**Chemical Propulsion Module**
Dry mass	365 kg	71 kg
Type of propellant	Xenon	N_20_4-MMH
Propellant mass	230/238 kg	156/334 kg
Electrical power @ 1 AU	5.5 kW	NA
Nominal thrust	0.17 or 0.34 N	4 kN
Number of thrusters	3 (1 or 2 in operation)	1

Total mass per launch	1229/1266 kg
Mass margin	23/19 %
Launches	Vehicles: Soyuz-Fregat - Range: Baikonur - Date: August 2009
Typical cruise duration	3.5 years (<2.5 years without Moon flyby, but mass margin ~ 5%)
Ground station	Perth, 35 m antenna, 8 hours/day
Priority technology research and development	• High-temperature thermal control materials • High-intensity and high-temperature solar generators • High-temperature X/Ka band antenna • High-temperature antenna pointing and despin mechanisms • Highly integrated control and data systems • Vision-based landing system

Note: first and second figures refer to MPO and MMO-MSE launches, respectively, unless specified otherwise
* with relay on MMO or MPO, respectively

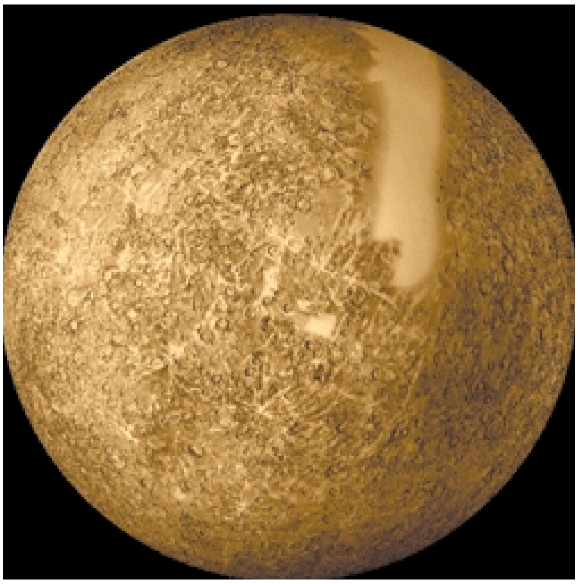


Figure 2: Hemisphere of Mercury imaged by Mariner 10 (composite image, no data from the blank areas). The other side of the planet has never been observed by a visiting spacecraft.

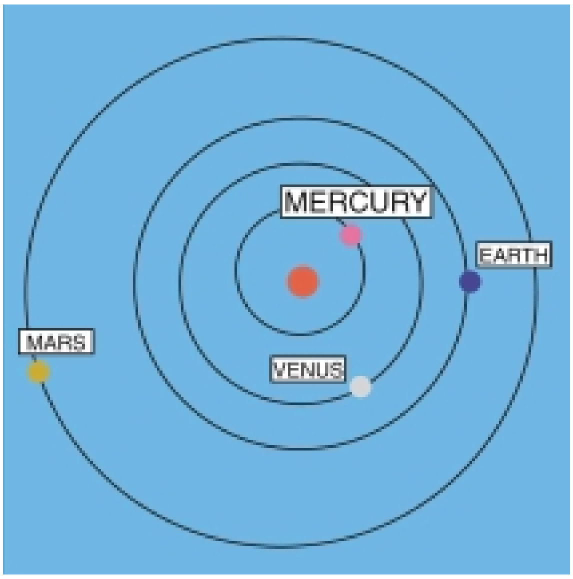


Figure 3: The terrestrial planets. They shared a common origin and so, to understand any one of them properly (including the Earth), planetary scientists must make sense of all four of them.

Some of the questions about Mercury as a planet that form the central rationale of this mission are:

- What will be found on the uninspected hemisphere of Mercury?
- How did the planet evolve geologically?
- Why is Mercury's density so high?
- What is its internal structure and is there a liquid outer core?
- What is the origin of Mercury's magnetic field?
- What is the chemical composition of the surface?
- Is there any water ice in the polar regions?
- Which volatile materials compose the vestigial atmosphere (exosphere)
- How does the planet's magnetic field interact with the solar wind?

BepiColombo's other objectives go beyond the exploration of the planet and its environment, to take advantage of Mercury's close proximity to the Sun:

- Fundamental science: Is Einstein's theory of gravity correct?
- Impact threat: What asteroids lurk on the sunward side of the Earth?

The scientific payload described here is a combination of high-priority instruments and forms a representative model that addresses the objectives of BepiColombo. These instruments do not necessarily constitute the final payload, but they have already been developed and, for the most part, flown; they therefore provide a set of realistic requirements for the system design, mission analysis, data links and flight operations.

The study has revealed that the best way to fulfil the scientific goals of the BepiColombo mission is to send two orbiters and one lander to Mercury:

- The Mercury Planetary Orbiter (MPO), a three-axis-stabilized and nadir-pointing module, revolves around the planet at a relatively low altitude and is dedicated to planet-wide remote sensing, radio science and asteroid observations.
- The Mercury Magnetospheric Orbiter (MMO), a spinner on a relatively eccentric orbit, accommodates mostly the field, wave and particle instruments.
- The Mercury Surface Element (MSE), a lander module, makes *in situ* physical, optical, chemical and mineralogical observations that serve also as ground-truth references for the remote-sensing measurements.

The method for transporting the spacecraft elements to their destinations emerges from a trade-off between mission cost and launch flexibility. It combines electrical propulsion, chemical propulsion and gravity assists. The interplanetary transfer is performed by a Solar Electric Propulsion Module (SEPM), which is jettisoned upon arrival. The orbit injection manoeuvres are then realized with a Chemical Propulsion Module (CPM), which is also jettisoned once the deployment of the spacecraft elements, MSE included, is completed.

A two-launch scenario, where the spacecraft elements are divided into two composites with nearly identical propulsion elements, is considered as the baseline for BepiColombo. The MPO and the MMO-MSE composites would be launched with two Soyuz-Fregats in 2009 and would reach Mercury in 3.5 years. The spacecraft concept is modular, however, and lends itself to a wide variety of schemes that would be compatible with the mission objectives. Alternative single- or split-launch scenarios with different schedules and other launchers, such as Ariane-5, could be selected at a later stage to comply with new programmatic and funding constraints.

2 Science Case

2.1 The Main Features of the Planet Mercury

Superficially Mercury looks like the Moon, but inherently it is quite different and many aspects of this planet remain controversial. Mercury also differs markedly from the other terrestrial planets, Venus, Earth and Mars. Distinctive features include the resonance of Mercury's spin and orbital periods, its composition and density, the state of its core, its magnetic field, the topography of its surface, its thin atmosphere and its magnetosphere.

The planetary bulk and orbital parameters of Mercury and Earth are compared in Tables 1 and 2.

Table 1: Mercury's bulk parameters.

Bulk Parameters	Mercury	Earth	Ratio Mercury/Earth
Mass (10^{24} kg)	0.3302	5.9736	0.0553
Volume (10^{10} km^3)	6.085	108.321	0.0562
Equatorial radius (km)	2440	6378	0.383
Ellipticity	0.0000	0.0034	0.000
Absolute mass density (g cm^{-3})	5.427	5.520	0.983
Uncompressed mass density (g cm^{-3})	5.3	4.1	1.3
Surface gravity (equator) (m s^{-2})	3.70	9.78	0.378
Escape velocity (km s^{-1})	4.3	11.2	0.384
GM (10^6 km^3 s^{-2})	0.02203	0.3986	0.0553
Bond albedo	0.056	0.385	0.145
Visual geometric albedo	0.11	0.367	0.300
Visual magnitude V(1,0)	-0.42	-3.86	-
Solar irradiance (W m^{-2})			
- at perihelion	14490	1418	9.786
- at aphelion	6290	1326	4.743
Black-body temperature (K)	442.5	247.3	1.789
Moment of inertia (C/MR^2)	0.33	0.3308	0.998
J_2 (10^{-6})	60	1082.63	0.055

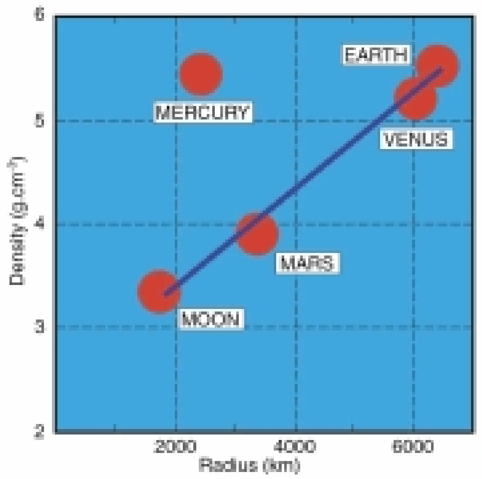
Table 2: Mercury's orbital parameters.

Orbital Parameters	Mercury	Earth	Ratio Mercury/Earth
Semi-major axis (10^6 km)	57.9	149.6	0.387
Perihelion (10^6 km)	46.0	147.1	0.313
Aphelion (10^6 km)	69.8	152.1	0.459
Eccentricity	0.2056	0.0167	12.311
Inclination to ecliptic (deg)	7.00	0.00	-
Mean orbital velocity (km s^{-1})	47.89	29.79	1.608
Sidereal orbital period (days)	87.969	365.256	0.241
Synodic period (days)	115.88	-	-
Sidereal rotation period (h)	1407.6	23.9345	58.785
Obliquity to orbit (deg)	~ 0.1	23.44	0.004

2.2 Planetology

Interior structure The density of Mercury is out of line with those of other terrestrial planets and the Moon (Figure 4). Reduced to standard conditions of gravitational compression, it is 5.3 g cm^{-3}, compared with only 4.1 g cm^{-3} for Earth and 3.8 g cm^{-3} for Mars. This peculiarity indicates that the concentration of iron is about twice that in Earth and it suggests an extremely large iron core radius that represents 70 to 80 % of the planetary radius (Figures 5 and 6).

Figure 4: Absolute densities of the terrestrial planets and the Moon.



Several different explanations have been proposed for Mercury's anomalously large iron core:

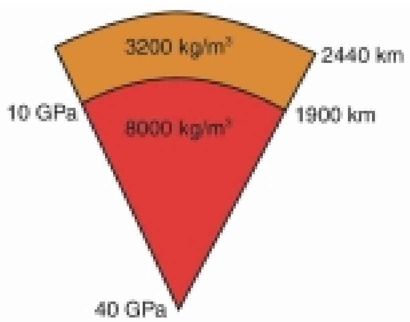
(a) Iron was more abundant in the zone of the pre-planetary solar nebula where Mercury accreted.

(b) Oxides were reduced to metallic form due to the proximity of the Sun.

(c) The temperature of the young Sun was sufficient to sublimate and blow off silicates, leaving only more refractory materials.

(d) The initial composition of the planet has been significantly altered by gigantic impacts that may have removed a substantial part of the mantle.

Figure 5. Simple, two-layer interior structure model of Mercury. Average mantle and core densities, central and core-mantle boundary pressures, surface and core radii are indicated.



Since the magnetic field is most likely generated by a hydrodynamic or thermoelectric dynamo, an outer shell of the core, perhaps 500 km thick, should be molten. Pure iron could not remain molten, with the cooling of the planet since its origin, but a small concentration of sulphur or other elements could depress the freezing point of the core alloy.

Gravity field and rotational state will reveal the planet's internal structure Knowledge about the structure of Mercury can be obtained by tracking the position and velocity of an orbiter and by measuring the rotational state of the planet. Low harmonics of the gravity field constrain the moments of inertia. The static part is controlled by the global shape while the time-dependent part is linked to the tidal deformation induced by the eccentricity of the orbit. Higher order terms yield information about inhomogeneities with scales commensurate with the orbiter altitude, such as variations of the crust thickness and density. A simulation of the gravity field experiment including random and systematic errors indicates that the signal to error ratio is larger than 10 for harmonic degrees up to 20.

To find the density profile as a function of depth, and to confirm or disprove the existence of a fluid outer core, the measurement of the gravitational field must be complemented by the determination of the obliquity and libration The obliquity, i.e. the angle made by the equator and the orbital plane, is estimated to be about 7 arcmin. The libration, or oscillation in longitude, results from the forcing torque acting on the equatorial asymmetric bulge, due to the orbit eccentricity. The libration is small for

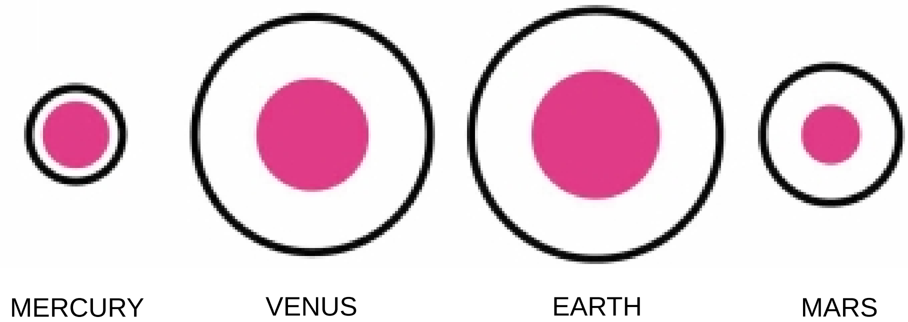


Figure 6. Comparison of the core sizes of the terrestrial planets

a rigid body and increases significantly if the mantle is decoupled from the core by a molten layer; its amplitude might reach a few 100 m at Mercury's equator.

Chemistry and mineralogy The global chemical mapping of the surface combined with the knowledge of the interior structure will provide answers to questions about the formation and composition of the planet.

The high density of Mercury suggests a core fraction at least twice that of Earth and a relative increase of the iron to silicon ratio by a factor of about five. On the other hand, the existence of the magnetic field requires the admixture of elements such as sulphur, silicon or oxygen to lower the melting point of the core material. However, metallic silicon is expected to exist only in oxygen-poor environments, and a high percentage of sulphur is unlikely because this element is volatile. There is indeed considerable evidence that the degree of oxidation and the abundance of volatile elements increase from Earth to Mars; the mantle abundance of FeO is 18 % at Mars and 7.5 % at Earth, and should be less than 5 % at Mercury.

The iron oxide and other volatiles contents of silicates are therefore indicators of the solar nebula temperature during accretion and should confirm that the chemical composition is related to heliocentric distance, unless Mercury did not accrete on its present orbit.

Some surface features reveal internal activity The evolution with time of internal activity, convection and volcanism, is constrained by the heat flow, at present estimated to lie in the range 10–30 mW m^{-2}. Models suggest that there may still be a partially molten asthenosphere under the lithosphere. Mercury's mantle is relatively thin and the volcanic activity is probably fed by cracks in the lithosphere tapping a partially molten layer, rather than by active upwelling. A giant volcanic dome, as suggested by recent Arecibo radar observations, is difficult to reconcile with this model. Small convection cells would tend to homogenise the tectonic pattern

Mercury does not seem to have been tectonically active recently. When the rotation period decreased to its present value, the relaxation of the equatorial bulge and the tidal stresses due to the eccentricity of the orbit created a network of lineaments. The contraction of the planet's radius by 1 to 2 km, due to the partial freezing of the core, is evidenced by lobate scarps resulting from thrust faults (Figure 7).

The intercrater plains are thought to have formed in a global resurfacing event 4 to 4.2 Ga ago, but their origin (lava flows or impact ejecta) is debated. The Caloris Basin is the closest equivalent to a lunar mare (Figure 8). A large impact there may have caused seismic waves that were focussed by the core and generated a pattern of hills and troughs at the antipode.

Other features tell of impacts and weathering The surface of Mercury has been shaped by the secondary flux of impactors that followed the main accretionary phase, 3.5 Ga ago (Figure 9). The collisional energy of impactors is relatively greater on Mercury than on any other terrestrial planet, because of the lack of an atmosphere and the large relative velocities between impactors and target.

The contribution of comet impacts should be markedly larger than for the Moon, due to the gravitational focusing effect of the Sun. Comets could be the source of the volatiles, possibly including water, that accumulated in polar craters never exposed to sunlight and have been observed in depolarized radar images obtained from Arecibo.

The present lack of high-resolution coverage of Mercury's surface limits our knowledge of the crater distribution to the larger sizes on about 40 % of the planet. Characterizing the population of small craters (100 m in diameter) will be essential for evaluating

Figure 7: Discovery scarp, one of the largest lobate scarps on Mercury, is shown in this Mariner 10 image. It is 5000 km from end to end and up to 2 km high (©NASA)

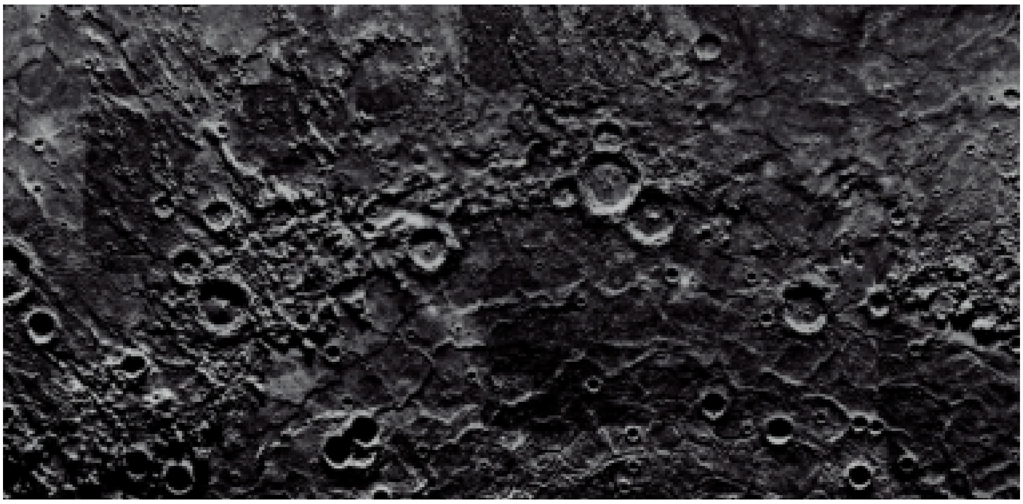
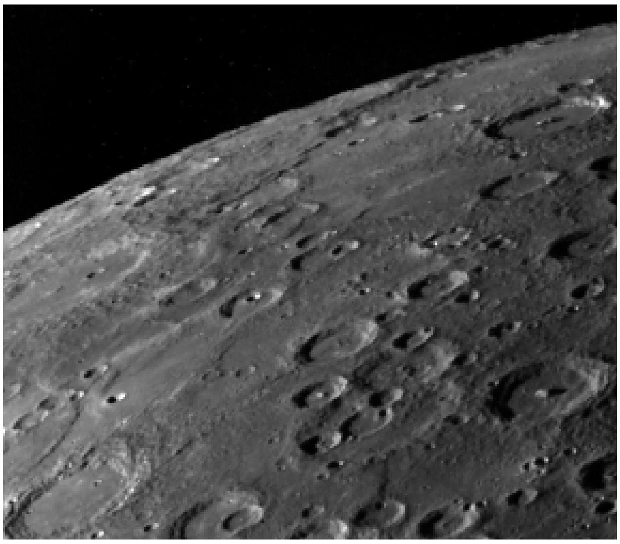


Figure 8: Mariner 10 image of part of the Caloris Basin. The floor is covered with smooth plains. Ridges form concentric rings around the centre of the basin (©NASA).

the relative ages of geological features with dimensions of a few km, such as lava flows, faults and major craters

A complex space weathering process involves the smallest impactors (micrometeoroids with sizes down to a few 100 µm) and bombardment by photons and charged particles. They are responsible for the fragmentation of grains, the formation of glasses and the reduction of iron into metallic form. The grain composition and size distribution has a major influence on the reflectance in the visible and near-infrared. The thickness of the regolith can be determined from the observation, with a spatial resolution of at least 10 m, of flat-floored craters, large enough to reach the bedrock but not to penetrate it.

Figure 9: As seen by the incoming Mariner 10 spacecraft, 25 years ago. (© NASA)



2.3 Particles and Fields

Mercury's magnetic field will be charted from a highly eccentric orbit Before the Mariner 10 flybys, it had been assumed that Mercury's core was frozen and could not support any dynamo. Contrary to expectations, the planet was found to have a small but significant magnetic field, about one hundredth of that of the Earth at the equator (Figure 10). Estimates of the equivalent magnetic dipole moment vary from 150 to 350 nT R_M^3, where R_M is the planet radius. The large uncertainty arises because the inversion of the measurements is ambiguous. A difficulty with interpreting the observations is that they result from the superposition of contributions internal and external to the planet.

Measurement of the total field with high accuracy and time resolution along a highly eccentric orbit will provide the raw data for determining the internal and external fields. The inversion of the data also requires accurate knowledge of the position of the spacecraft with respect to the planet. The expected temporal and seasonal variability of the magnetospheric current systems implies the need to perform these measurements over at least two Mercury years.

Gas in the planet's vicinity As Mercury has no stable atmosphere, the gaseous environment is best described as an exosphere. The total column density is less than 10^{12} cm^{-2} and the mean free paths are large. The exosphere is variable, as a function of the hermean day, distance from the Sun and solar and magnetospheric activity. The existence of five elements, O, H, He, Na and K, has been established, the first three by Mariner 10, the last two by ground-based observations. It is highly probable that other elements are also present. In addition, the possible presence of ice near the poles could contribute further volatiles to the exosphere.

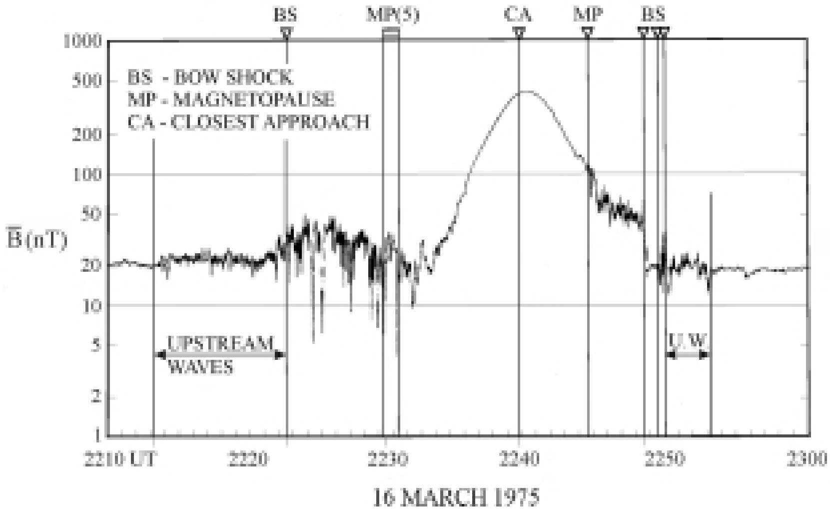


Figure 10: Modulus of the magnetic field observed during the third Mariner 10 flyby (after Ness et al., Icarus, 28, 479, 1976).

The key questions concern the production and loss mechanisms, their temporal and spatial dependence, coupled with elemental composition of the source materials. Production mechanisms include photo- and ion sputtering, impact vaporisation by in-falling micrometeorites, photon-stimulated desorption, and diffusion through the regolith. The main loss processes are photoionisation and charge exchange; at high altitudes, radiation-pressure-driven ballistic transport also plays a role in redistributing some exospheric constituents. Additionally, the constituents sputtered by the impact of energetic magnetospheric particles may have velocities in excess of the escape velocity (Figure 11).

The level of ionisation of Mercury's exosphere is very low: both theoretical models and Mariner 10 observations suggest plasma densities of the order 0.1 to 1 cm^{-3}.

Mercury's distinctive and puzzling magnetosphere The Mariner 10 first and third flybys showed that Mercury possesses a magnetosphere. The bow shock and magnetopause crossings were detected at locations in approximate agreement with the calculated overall shape of the magnetosphere. Substorm-like features were also detected, as were VLF radio waves and field-aligned currents.

The size of Mercury's magnetosphere is only about 5% of that of Earth, although the planetary radii differ by less than a factor three. This means that Mercury occupies a much larger relative volume inside its magnetosphere (Figure 12). On the sunward side the magnetopause is at most only half the planet's radius above the surface. The difference between the scale sizes leads to significant differences in the dynamics of the two magnetospheres.

The Earth's ionosphere provides a conductive anchor for the magnetic field lines or, equivalently, a good conductor for the currents needed to sustain the shape and dynamics of the magnetosphere. The absence of an ionosphere at Mercury poses a significant problem for the closure of the magnetospheric current system. Although difficult to visualize, closure might be established via the ionized component of the exosphere, the planetary regolith or a sheath of photo-electrons on the sunlit side. A better understanding of the magnetospheric current systems requires more information about the conductivities of the surface and exosphere.

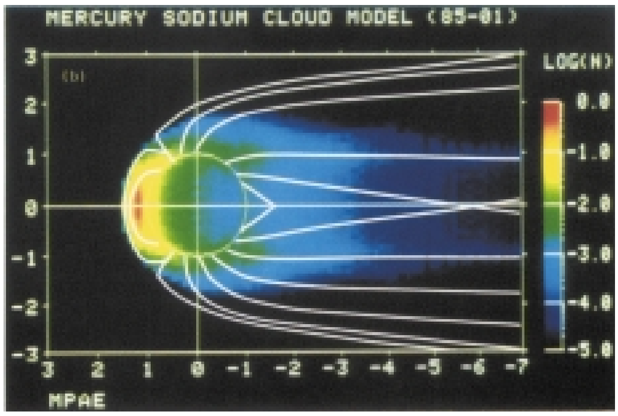


Figure 11: Model Na atom density (cm^{-3}) around Mercury for an ejection velocity of 3 km s^{-1} with magnetic field line overlay (Ip, Geophys. Res. Lett, 13(5), 423,1986).

The solar wind may reach the planet's surface, at least at times of fast-changing pressure and interplanetary magnetic field configuration. This may have been observed indirectly by Mariner 10 during its first flyby. A major uncertainty arises for all modelling work if, at least occasionally, the magnetospheric current systems have topologies significantly different from those observed at Earth.

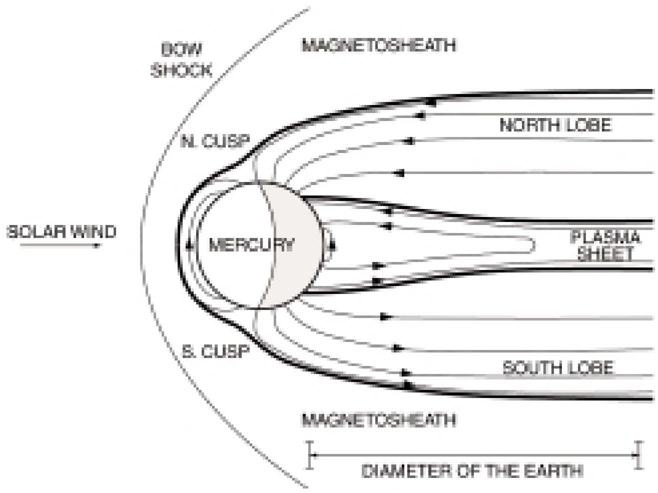


Figure 12: The magnetosphere of Mercury (Slavin et al., Planet. Space Sci, 45, 133 1997).

2.4 Relativity and Gravitational Physics

Deep in the solar gravitational field, Mercury is more affected by relativistic effects than any other planet. Famously, its orbit swivels around the Sun in a manner not visualized in Newtonian theory, advancing the planet's perihelion by 43 arcsec per century. Einstein explained the phenomenon in terms of space-time curvature in his theory of general relativity (GR). The BepiColombo mission to Mercury offers unique possibilities for testing GR and exploring the limits of other theories of gravitation, with unprecedented accuracy. The discovery of any violation of GR would have profound consequences in theoretical physics and cosmology.

Tracking of the Viking landers on the surface of Mars showed that GR describes gravitational phenomena to a level of accuracy of at least 10^{-3}, but no significant breakthrough has been made during the last 20 years. The use of higher frequencies in deep-space telecommunications offers the potential for substantial improvements with only minor additions to the instrumentation of BepiColombo and little increase in mission complexity.

In the weak-field, small-velocity approximation, metric theories of gravity are classified using the parametrized post-Newtonian formalism. In the simplest case, which assumes an isotropic universe and conservation of energy and angular momentum, classification is based on only two parameters, β and γ, both assumed equal to unity in GR. The parameter β is associated with the amount of non-linearity in the superposition law for gravity, and γ measures the space curvature produced by a unit mass.

The current determination of β and γ relies on the observation of celestial bodies, mostly Mercury and the Moon, and the propagation of electromagnetic waves. Precision measurements of range and range-rate will constrain the position of Mercury's centre of mass within 1 m and that of BepiColombo within a few cm, leading to the accurate determination of β and γ from the orbital elements of the planet and the time delay experienced by radio signals as they propagate between Earth and Mercury. Solar gravity also affects the frequency of a wave and the Doppler effect provides a novel observable quantity and an independent determination of γ.

Measuring the nodal precession of the planet's orbital plane will give (or put upper limits on) the quadrupole moment of the Sun, J_2, and the rotation of the solar core with respect to the photosphere. A possible time variation of the gravitational "constant" G might also be detected from the quadratic drift in time of Mercury's mean anomaly.

Finally, the precise determination of Mercury's motion will also test the very strong equivalence principle through the Nordvedt effect and yield an estimate of the controlling parameter, γ. This measurement can be profitably used to remove the high correlation between β and J_2.

An accelerometer and a transponder can make the spacecraft virtually immune to plasma noise and non-gravitational perturbations. A complete simulation of BepiColombo's radio science experiments, using realistic noise models (including systematic effects) indicates that an improvement of 1-2 orders of magnitude is possible, in the determination of all measured parameters (Table 3).

2.5 Near-Earth Objects

The risk of impacts on the Earth by asteroids and comets has aroused scientific and governmental concern, and stimulated worldwide efforts to detect Near-Earth Objects (NEOs). A telescope on BepiColombo's Mercury Planetary Orbiter (MPO) will provide a fresh perspective on NEOs, and a unique opportunity to discover a predicted new class of potentially hazardous asteroids.

Well-known classes of asteroids in the inner Solar System are Atens, Apollos and Amors. Atens are of special interest for BepiColombo. They have orbits with semi-major axes smaller than 1 AU and aphelion distances greater than 0.987 AU. Numerical simulations have shown that Atens may evolve dynamically into a new class of asteroids with aphelia just inside the orbit of the Earth. These Inner Earth Objects (IEOs) have not yet been detected.

With orbits that supposedly lie entirely inside the Earth's orbit, IEOs are hard to observe from the ground or from a space observatory near the Earth. They are often near to the Sun in the sky, and present a partly dark cross section to the would-be observer. Even if spotted from the Earth, an IEO could easily be lost again before sufficient observations had determined its orbit.

From Mercury, on the other hand, the IEOs are seen against a dark sky background, well lit by the Sun. Numerical simulations and modelling indicate that a small telescope with a large field of view, able to reach an apparent magnitude of 18 in a few tens of seconds, could observe more than 80% of the Atens and also detect the presumed IEOs with aphelia between the orbits of Venus and Earth.

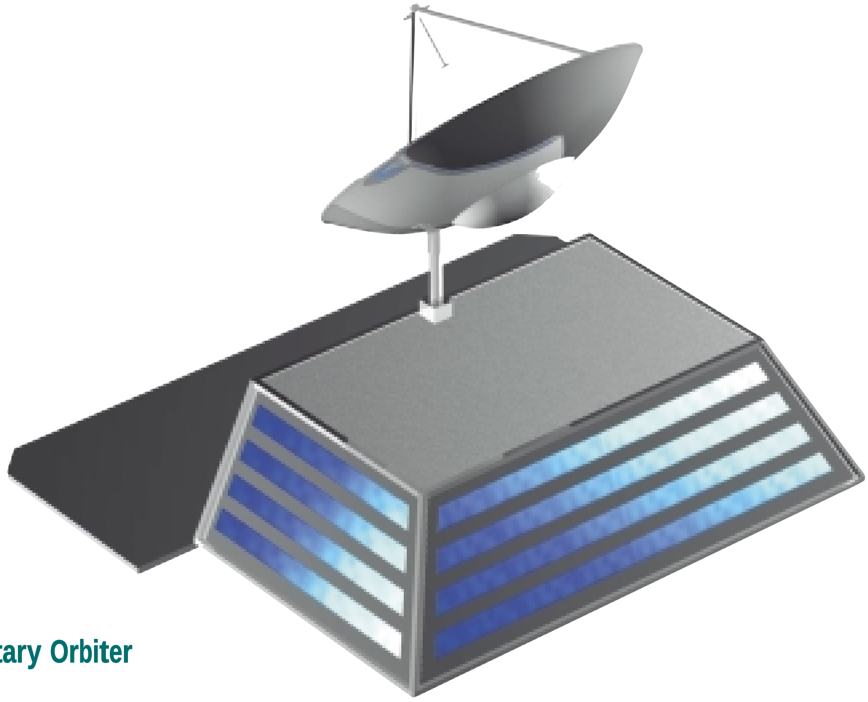
Parameter	Present accuracy	BepiColombo
γ	10^{-3}	2.5×10^{-6}
β	7×10^{-4}	5×10^{-6}
η	10^{-3}	2×10^{-5}
J_2	10^{-7} (indirect)	2×10^{-9}
d(lnG)/dt	2×10^{-12} year^{-1}	3×10^{-13} year^{-1}

Table 3: Accuracies of the gravitational tests with BepiColombo derived from a simulation including gaussian noise and systematic errors, with calibration of plasma noise and non-gravitational perturbations to a level of 10^{-3}-10^{-2}.

It will be sufficient to monitor a strip on the sky of 6° by 360°, with a telescope observing along the direction of motion on a polar-orbiting spacecraft. All objects must cross this strip at least twice along their orbits. Even taking into account the difference in apparent magnitude at the two crossings, a large fraction of these objects would be imaged and their orbits determined.

The same telescope will also observe many asteroids of the other two types (Apollo and Amor) when they are sufficiently close. Preliminary evaluations indicate that there could be a total of some 100 objects in the selected strip of sky at any one time. Such an instrument on BepiColombo will therefore provide a better understanding of the entire NEO population and the threat it poses to life on Earth.

3 Spacecraft and Payloads



3.1 Planetary Orbiter

Figure 13: The planetary orbiter.

Payload overview The planetary orbiter (MPO) carries instruments devoted to (1) close range studies of the surface, (2) measurements of the gravity field and rotational state, (3) tests of general relativity and fundamental science and (4) observations of Near-Earth Objects.

The spacecraft orbit and configuration are driven by scientific requirements and environmental constraints (Figure 13).

The orbit is polar to facilitate global mapping and as low as possible to optimize spatial resolution. The periapsis and apoapsis altitudes are 400 km and 1500 km, respectively. MPO is three-axis-stabilized. Most remote-sensing instruments have their apertures in the base of the spacecraft body and point constantly along the nadir direction for a continuous observation of the surface. The total data volume collected by MPO is 1550 Gb for a nominal lifetime of 1 year. The characteristic features and requirements of the instruments are summarized in Table 4 and the relevance of the payload to the scientific objectives is outlined in Table 5.

Imaging system The wide angle camera (WAC) performs a global mapping of the surface with a resolution better than 200 m, using a two-dimensional CCD (Charge Coupled Device) detector. Imaging the entire surface at a scale of 100 m per

Instrument	Acronym	Range	Mass (kg)	Average power (W)
Narrow angle camera	NAC	350-1050 nm	12	16
Wide angle camera	WAC	350-1050 nm		
IR spectrometer	IRS	0.8-2.8 µm	6	10
UV spectrometer	ALI	70-330 nm	3.5	3
X-ray spectrometer	MXS	0.5-10 keV	4.5	8
Gamma-ray spectrometer	MGS	0.1-8 MeV	7.5	5
Neutron spectrometer	MNS	0.01-5 MeV	5	3
Radioscience:	RAD			
- Transponder	KAT	32-34 GHz	3.5	9
- Accelerometer	ISA	10^{-4}-10 Hz	8	6.3
Laser altimeter*	TOP	1064 ±5 nm	6.5	10
Telescope*	NET	18 mag	8	15

* Not included in the reference payload for the satellite design exercise.

Table 4: MPO instrument summary.

Scientific objective	NAC	WAC	IRS	ALI	MXS	MGS	MNS	RAD	TOP	NET
Morphology	X	X						X	X	
Internal structure								X		X
Composition				X	X	X	X			
Mineralogy	X	X	X							
Exosphere		X		X						
Fundamental science								X		
Near-Earth Objects										X

Table 5: Relevance of the MPO payload to BepiColombo's scientific objectives.

pixel requires a minimum of 7.5 x 10^9 pixels (excluding swath overlap), which must be multiplied by a factor of 2.5 to account for colour information. Assuming a compression of 2 bits per pixel gives a total requirement of around 75 Gb, which should be compared with a nominal total data volume of 1550 Gb. A higher resolution might be considered.

The narrow angle camera (NAC) will explore selected surface features at a resolution better than 20 m. This line-scan device makes use of a linear CCD array of at least 2048 pixels. At the highest resolution, 10 m per pixel, 5% of the surface equates to 37 x 10^9 pixels. Assuming 2 bits per pixel after compression and a factor of 2.5 for colour information gives a total data volume of around 150 Gb, which corresponds to less than 10% of the total available data volume.

Infrared spectrometer The near- and thermal-infrared range contains the absorption bands of most major rock-forming minerals. The main function of the infrared mapping spectrometer (IRS) is to provide mineralogical maps with a spectral resolution of 128 channels in the bandwidth 0.8 - 2.8 µm to be combined with the lower resolution elemental maps provided by gamma and

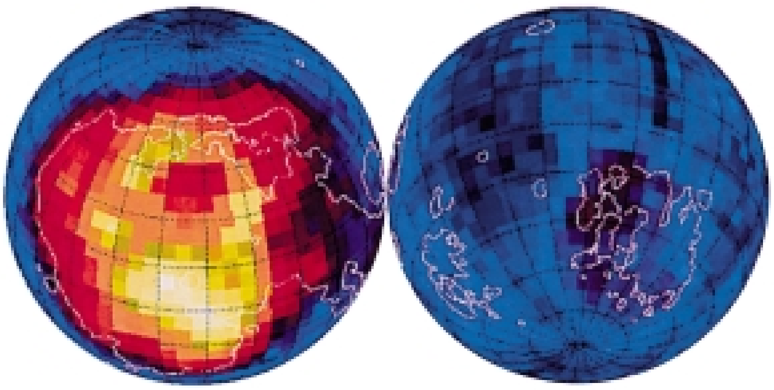


Figure 14: Gamma-ray thorium count map of the Moon, produced by the Lunar Prospector team, Los Alamos National Laboratory, USA.

X-ray spectrometries. The IRS angular resolution of 0.5 mrad corresponds to pixel sizes of 150 m and 1.25 km at low and high altitudes, respectively. Assuming a pixel size of 1.25 km^2, an overlap factor of 2 and a resolution of 12 bits with a compression factor of 8, yields a data volume of 23 Gb for 128 channels. This data volume is quite compatible with the capability of the telemetry link.

Ultraviolet spectrometer Most neutral metals, some of their ions, and several key radicals have strong resonance transitions in the mid-ultraviolet region. Airglow spectrometers detect the column density of a given species by looking over the limb of the planet, provided that the photon scattering coefficient, i.e. the product of the solar flux at the line and the transition probability, is sufficiently large. A tiltable mirror is therefore required. The UV spectrometer (ALI) will not only detect and determine the abundances of Al, S, Na and OH in the exosphere, but will also perform UV photometry on the surface of the planet. The light is dispersed in the focal plane, where a UV-sensitive photon-counting microchannel plate detector records the spectrum.

Gamma-ray, X-ray and neutron spectrometers A planetary body without an atmosphere is exposed to galactic cosmic rays (GCR) and solar X-rays. Both types of radiation excite secondary radiation in the surface that is partially emitted into space. Measurement of gamma and X-rays, as well as neutrons, from an orbiter can provide both the qualitative and quantitative elemental compositions of the surface. These data can then be displayed in the form of elemental concentration maps (Figure 14).

The bombardment of the surface by GCR generates a nuclear cascade of secondary particles, with energetic neutrons as the most abundant species. The moderation of these neutrons depends strongly on the composition of the material, particularly the H content. Gamma rays are produced by neutron reactions; their flux is a function of the chemical composition and results from the decay of radioactive elements.

Several types of detectors are available for a gamma-ray spectrometer (MGS). Germanium offers the best energy resolution, but must be cooled down to about -170°C for optimum performance. A germanium crystal accumulates radiation damage because of GCR bombardment and its energy resolution degrades with time. The nominal resolution can be recovered by heating up the crystal to +100°C for tens of hours. Scintillation detectors with low energy resolution, such as NaI or CsI crystals, operate at much higher temperatures but have a reduced sensitivity.

An X-ray spectrometer (MXS) is very appropriate in the case of Mercury because of the proximity of the Sun and the larger flux of X-rays. The solar output

Table 6: Comparative merits of gamma-ray, X-ray and neutron spectrometers.

Spectrometer	Gamma-ray	X-ray	Neutron
Sensing depth	≃10 cm	≃ 1 µm	≃ 100 cm
Angular resolution	≃1 rad	≃ 0.1 rad	≃ 1 rad
Elements	K, Th, U, O, Mg, Al, Si, Ca, Ti, Fe, H, C	Mg, Al, Si, Ca, Fe	NA

is highly variable and must be monitored. Solid-state or gas proportional counter detectors can be used to detect X-rays at room-temperature with rather good energy resolution.

A neutron spectrometer (MNS) is more sensitive to change in elemental composition but cannot identify the elements. Both spectrometers, MNS and MXS, are complementary.

The main characteristics of these three detectors are compared in Table 6. The data volume to be transmitted to Earth is of little significance compared to the capability of the telemetry link.

Radioscience experiments The radioscience experiments (RAD) involve many instruments and spacecraft subsystems as well as the ground antennas to perform four classes of measurements:

- The rotation state of Mercury (size and physical state of the core).
- The global structure of the gravity field and tidal effects (internal structure).
- The local gravitational anomalies (mantle and its interface with the core).
- Orbital parameters of Mercury and wave propagation between Earth and Mercury (general relativity, gravitational constant, oblateness of the Sun).

The observable quantities are:

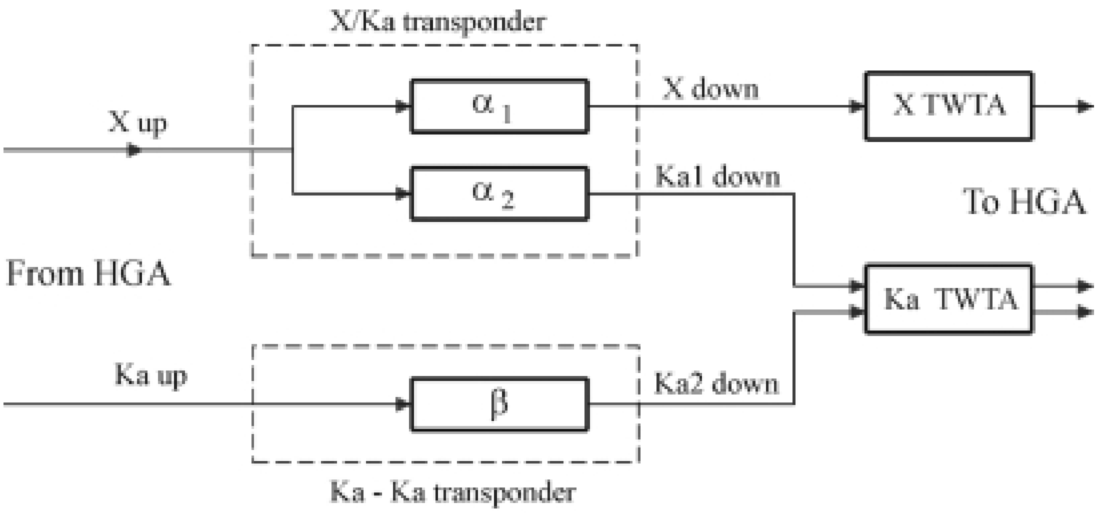
- The range and range-rate between the ground antenna and the spacecraft, using the onboard radio-frequency subsystem and a dedicated transponder (KAT, Figure 15).
- The non-gravitational perturbations acting on the spacecraft measured with an accelerometer (ISA).
- The absolute attitude of the spacecraft measured with a star tracker or a telescope (NET).
- The longitudinal displacement of surface features derived from the comparison of images collected during successive orbits by the high-resolution camera (NAC).

Laser altimeter Knowledge of the topography is required for a geological interpretation of surface images and gravity data. The correlation between the topography and the gravity field will assess the degree of isostatic compensation of crustal units, give an estimate of crust thickness variations, and detect ancient crustal structures buried by younger lava flows.

The telescope has an aperture of 25 cm; combining the altimeter with the camera could reduce the mass by 2-3 kg. The data volume generated by the altimeter is small since only a precise time stamp and the measured range have to be transferred for each shot.

NEO detection system The Near-Earth Objects telescope (NET) is accommodated on the radiator side of the spacecraft. Its optical axis is tangential to

Figure 15: Block diagram and transponding ratios of the radio frequency subsystem. The Ka-Ka transponder is a radio science instrument; the X/Ka transponder, travelling wave tube amplifiers (TWTA) and high-gain antenna (HGA) are parts of the spacecraft telecommunication subsystem.



the orbital trajectory and describes a great circle on the celestial sphere in 2.3 h. The field drift of 156 arcsec/s is compensated by operating the camera in a time-delayed integration mode, in which the charge of each pixel is shifted along the detector columns in synchronism with the orbital motion. In this way, the camera continuously scans a swath of 2° with an effective exposure time of 48 s. By rotating the spacecraft around the nadir axis by ±3° it will be possible to cover a strip of 6° in three consecutive revolutions. The input beam is reflected with a mirror placed in front of the entrance pupil, which also acts as a cover to protect the telescope from direct sunlight during spacecraft manoeuvres.

Table 7: Characteristics of the Near-Earth Objects telescope.

Design	Maksutov-Cassegrain	Vmag	S/N
Focal length	880 mm	14.0	173.3
Aperture	200 mm	15.0	97.3
Focal ratio	1:4.4	16.0	49.8
CCD	2048 x 2048	17.0	23.0
Pixel size	15 µm	18.0	9.9
Field of view	2°	19.0	4.1

The positions of the light sources are evaluated in real-time by the on-board data-processing unit, concurrently with the scanning operation; the detection of moving objects is performed on the ground. No image is stored, only the positions of the sources are telemetered to ground.

The characteristics and performances of the instrument are given in Table 7. The assumptions for the estimation of the signal-to noise ratio (S/N) for a given visual magnitude (Vmag) are: exposure time, 48 s; CCD readout noise, 20 electrons; average CCD quantum efficiency, 40% over the range 450-850 nm; telescope optical throughput, 60%; sky brightness, 21.5 mag/arcsec^2; point spread function distributed over 9 pixels.

3.2 Magnetospheric Orbiter

Payload overview The magnetospheric orbiter (MMO) is mostly dedicated to the study of the wave and particle environment of the planet (Figure 16). This spacecraft is spin-stabilized at 15 rpm, which facilitates the azimuthal scan of the detectors and the deployment of the wire electric antenna; the spin axis is perpendicular to the equator. The orbit is polar and highly elliptic; its major axis lies in the equatorial plane to permit a global exploration of the magnetosphere from an altitude of 400 km up to a planetocentric distance of nearly 6 planetary radii.

The total data volume collected by MMO is 160 Gb during a nominal lifetime of 1 year.

The operation of the field, wave and particle instrument complement is managed by a central payload interface unit (CPIU), which acts as a single interface for the transmission of scientific data and the reception of commands. CPIU also provides secondary power to the instruments (Figure 17).

The main features of the MMO instruments are summarized in Table 8; the relevance of the model payload to the mission objectives is shown in Table 9.

A camera also forms part of the MMO payload as a back-up for the MPO imagers. It may also be advantageous to complement the proposed suite of

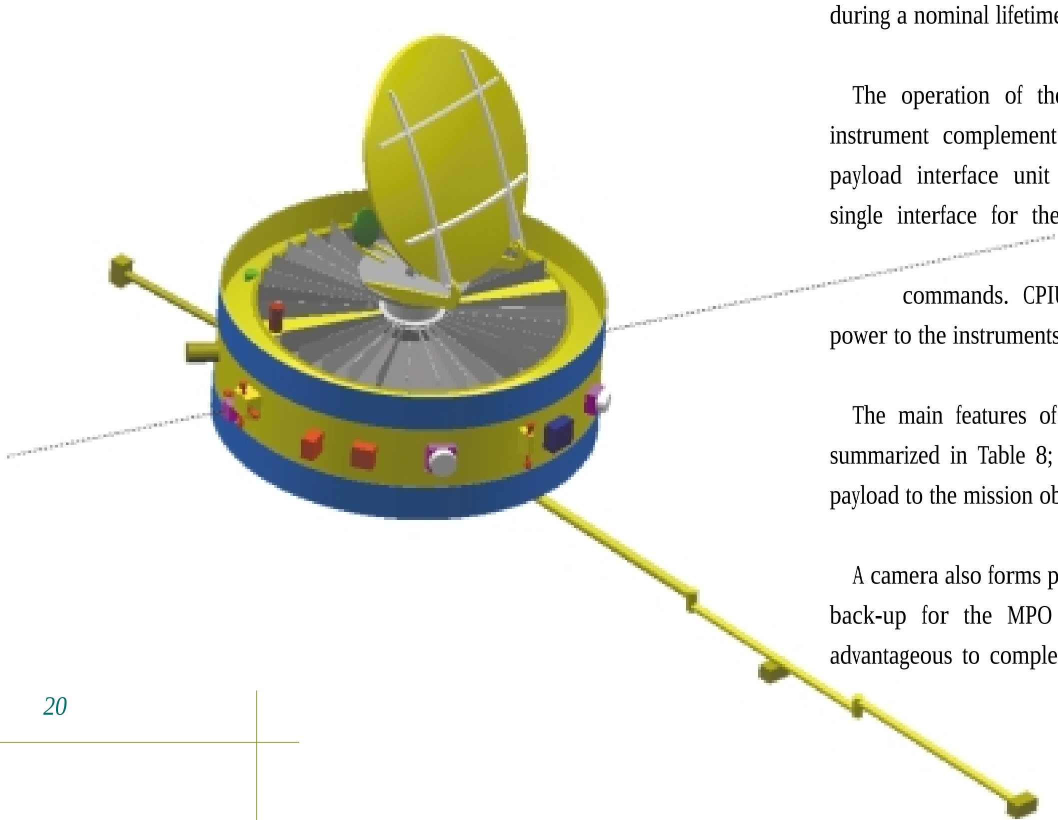


Figure 16: The magnetospheric orbiter.

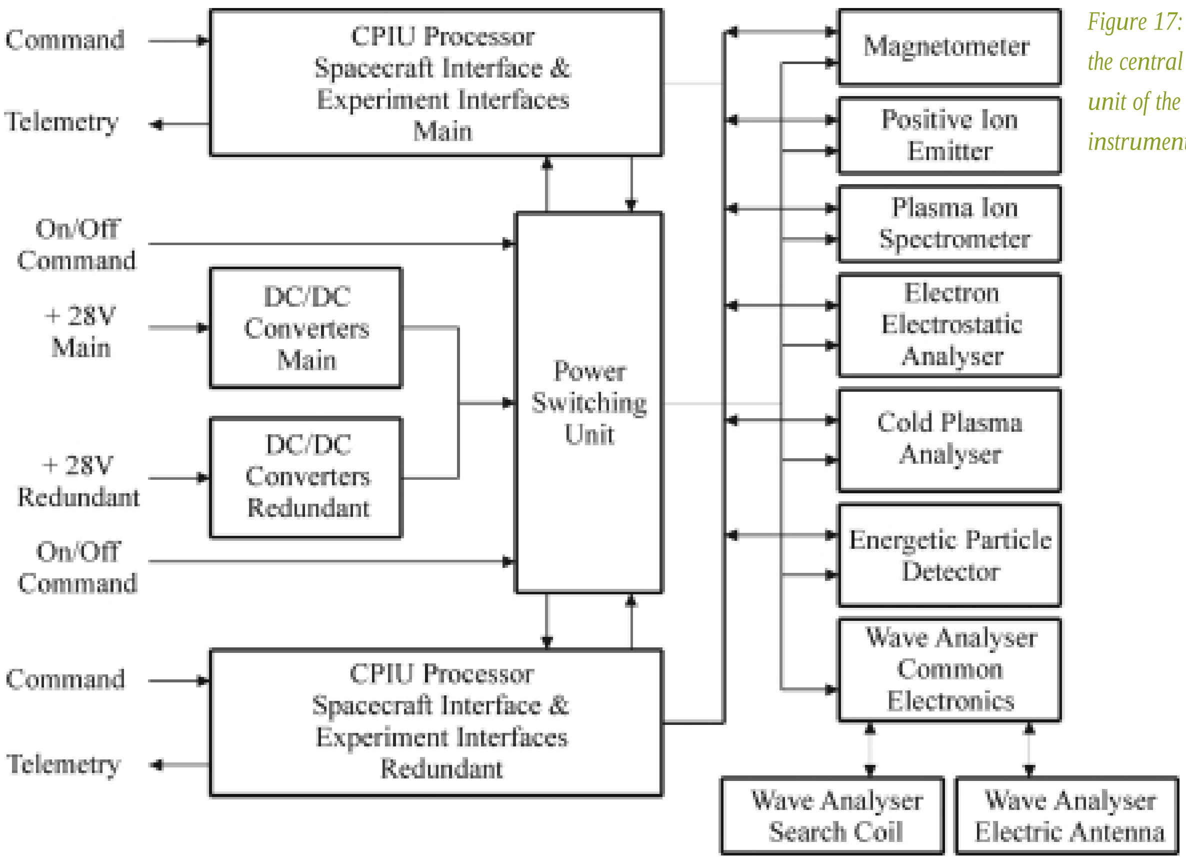


Figure 17: Block diagram of the central payload interface unit of the particle and field instruments.

instruments with an energetic neutral imager to visualize the magnetosphere of Mercury.

Magnetometer Of the different magnetometers utilised in space research, only the fluxgate sensors are intrinsically able to withstand the severe thermal environment in Mercury orbit. These magnetometers have been used with considerable success in all deep-space and planetary probes. They are also rugged and reliable. No special development is required beyond the optimisation of the mechanical construction for the high-temperature environment. The Curie temperature of the material used for the fluxgate sensors is in excess of 600 ºC; thus the basic sensor is fully qualifiable for this mission. Two tri-axial sensors, especially optimised for the Mercury environment are mounted on one of the radial booms.

Charged-particle detectors The set of charged-particle detectors (IMS, EEA, CPA and EPD) covers a combined energy range of several 100 keV.

Instruments	Acronym	Range	Mass (kg)	Average power (W)
Magnetometer	MAG	± 4096 nT	0.88	0.35
Ion spectrometer	IMS	50 eV–35 keV	4.4	4
Electron analyser	EEA	0–30 keV	1.1	1.2
Cold plasma detector	CPA	0–50 eV	1.3	1.9
Energetic particle detector	EPD	30–300 keV	1.2	0.7
Search coil	RPW-H	0.1 Hz–1 MHz	5.1	4
Electric antenna	RPW-E	0.1 Hz–16 MHz		
Central interface unit	CPIU		2.1	1
Positive ion emitter	PIE	1–100 μA	2.7	3.8
Camera	SCAM	350–1000 nm	8	12

Table 8: MMO instrument summary.

The three-dimensional ion mass spectrometer (IMS) consists of a plasma module and a heavy-ion module. The nature of each ion species, its mass, charge and energy distribution are completely defined. The output of the ion channel is compressed and the moments of the energy distribution measured with the plasma channel are evaluated on-board to limit the amount of data transmitted to ground.

Scientific objective	MAG	IMS	EEA	CPA	EPD	RPW-H	RPW -E	PIE	SCAM
Morphology									X
Structure	X								
Composition		X							
Mineralogy									X
Exosphere		X	X	X					X
Magnetosphere	X	X	X	X	X	X	X	X	
Solar wind	X	X	X	X	X	X	X	X	

Table 9: Relevance of the MMO payload to BepiColombo's scientific objectives

The electron electrostatic analyser (EEA) measures the three-dimensional distribution of the plasma electrons. A data-processing algorithm also generates the moments of the distribution function, up to the heat flux tensor to match the acquired data volume to the available telemetry rate.

The cold plasma analyser (CPA) measures the energy and composition of the low energy ions. As for EEA, the head of the instrument protrudes outside the spacecraft and requires a careful thermal design; the potential of the spacecraft should be controlled, or at least known with an accuracy better than 1 V, for a correct interpretation of the distribution functions in the low energy range.

The energetic plasma detector (EPD) extends the energy range for magnetospheric particles up to several MeV. It is suited to the observation of ions and electrons associated with substorm injection events or trapped in the planetary magnetic field. An additional objective is to study the solar energetic particles, the galactic cosmic rays, the Jovian electrons and the interplanetary medium, which are characterized by distinct energy spectra, fluxes and compositions.

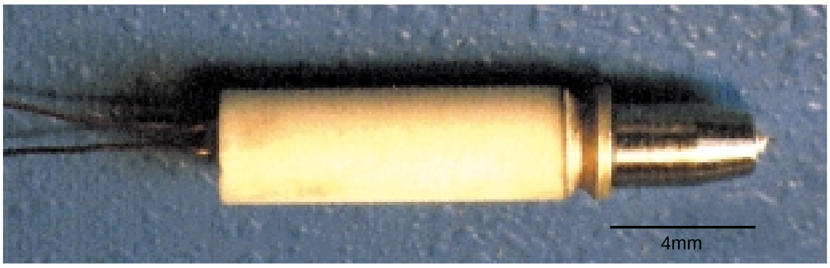


Figure 18: Positive ion emitter without container and extracting electrode. The emitting needle (not visible) is located at the tip of the emitter on the right hand side and the wires on the left are connected to the indium reservoir heater.

Wave receiver The instrument consists of a tri-axis search-coil magnetometer deployed on a boom and a one-axis electric antenna, made of two 35 m wires extending radially in the spin-plane. The radio- and plasma-wave investigation will survey magnetospheric phenomena, detect and localize radio emission sources and monitor the solar activity.

Positive ion emitter In a tenuous plasma environment, such as the magnetosphere of Mercury, the spacecraft floating potential may reach positive values of several tens of volts. This phenomenon is due to the electron emission induced by solar photon bombardment on the surface. A large spacecraft potential and the presence of a photoelectron cloud strongly perturb the measurement of the ambient plasma parameters. It is possible, however, to release the positive charge accumulated on the surface with a positive indium ion emitter (PIE), provided the spacecraft is conductive and equipotential; the ion current required for reducing the potential to about one volt is of the order of several tens of μA (Figure 18).

Imaging system A camera with a resolution of 10-20 m per pixel at periapsis (SCAM) provides additional imaging information beyond that given by MPO by using different filters and phase angles.

A camera optimised for a spinning spacecraft can follow a design similar to that adopted for the Halley multicolour camera flown on ESA's Giotto spacecraft. The CCD detector is masked, except for a few open lines, and is operated in a time-delayed

integration mode; as the scene moves across the detector because of the spin, the CCD is clocked at the rate of motion to produce a two-dimensional image. The spin of the spacecraft and the orbital motion lead to rectangular images that map back to distorted annuli on the surface; this requires an accurate reconstruction algorithm. A mirror mounted at 45° with respect to the telescope axis can be rotated so that, in combination with the spin of the spacecraft, any surface feature can be observed.

3.3 Surface Element

Payload overview The lander (MSE) will explore a sample area of the planetary surface with the maximum possible resolution and perform local measurements against which the data collected by the orbiters can be validated (Figure 19).

A list of instruments and their relevance to the scientific objectives are given in Tables 10 and 11. The data volume collected by MSE is 75 Mb for a nominal lifetime of 1 week.

MSE can carry up to 7 kg of scientific hardware and additional, or alternative, instruments can be included in the model payload. A camera mounted on the rover would perform a close examination of rocks and regolith. Very simple sensors could measure the electric conductivities of the ground and of the exosphere, which are crucial parameters for understanding the current patterns that shape the magnetosphere.

Heat flow and physical properties package The sensors of the heat flow and physical properties package (HP^3) are mounted in a penetrating device, or mole; they consist of a string of thermistors that can be electrically heated, an accelerometer and a radiation densitometer. HP^3 measures the surface properties such as temperature, thermal conductivity and diffusivity, bulk density and mechanical hardness as a function of depth, down to about 2 to 3 m.

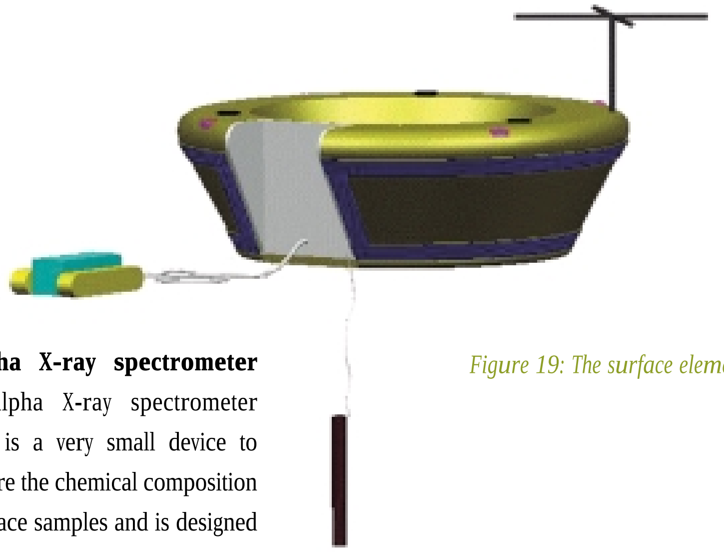


Figure 19: The surface element.

Alpha X-ray spectrometer The alpha X-ray spectrometer (AXS) is a very small device to measure the chemical composition of surface samples and is designed to be transported by a rover. AXS contains a set of Cm-244 sources that emit energetic alpha particles which are backscattered or induce X-ray emission from the sample. The X-ray mode is sensitive to Na, Mg, Al, Si, K, Ca, Fe, P, S, Cl, Ti, Cr, Mn and Ni, the alpha mode to C and O. The sampling depth is about 10 µm and the integration time is 1 to 2 h per sample. Such an instrument made the first in-situ analysis of martian rocks.

Imaging system The imaging system on MSE includes a descent camera with a four-position filter wheel (CLAM-D) which will take its last image a few 100 m above the surface, a panorama camera (CLAM-S) to characterize the surface at the landing site and, possibly, a close-up imager on the rover; CLAM-S consists of 4 pairs of micro-cameras for a full stereoscopic coverage of the 360° field of view around the lander, with the possible exception of one quadrant, depending upon solar elevation. A data volume of 68 Mb is dedicated to imaging.

Magnetometer A magnetometer on the lander (MLMAG) will characterize the magnetic properties of the surface and provide a reference for models of the intrinsic planetary field. It will also be possible to derive the electric conductivity of the ground by simultaneously recording the magnetic field fluctuations on MMO and MSE.

Instrument	Acronym	Deployment	Mass (kg)	Average power (W)
Heat flow and physical properties	HP³	Mole	1	0.3
Alpha X-ray spectrometer	AXS	Micro-rover	0.8	1
Descent camera	CLAM-D	None	0.5	3
Surface camera	CLAM-S	None	0.2	3
Magnetometer	MLMAG	None	0.5	0.6
Seismometer	SEISMO	None	0.9	0.6
Mole	MDD	-	0.4	5
Micro-rover	MMR	-	2	3

Objective	HP³	AXS	CLAM-D CLAM-S	MLMAG	SEISMO
Morphology			X		
Structure	X			X	X
Composition	X	X			
Mineralogy	X		X		

Table 10 (top): MSE instrument summary.

Table 11(bottom): Relevance of the MSE payload to BepiColombo's objectives.

Figure 20: The mico-rover "Nanokhod".

Figure 21: The mole during a field test.

Seismometer A seismometer (SEISMO) is tentatively considered because it would significantly enhance the science return, especially if the lifetime of MSE could be increased beyond 1 week. This instrument would record tidal deformations and sound waves excited by quakes in the crust or in the mantle of the planet.

Deployment devices A soil-penetrating device (MDD) and a micro-rover (MMR) are required for the deployment of some instruments. The mole is derived from the Russian Mars programme and reaches depths of several metres in a regolith. A rover attached to a tether can deploy instruments at selected sites several metres away from the lander. Like most of the hardware in the model payload of BepiColombo, the mole and the rover are in very advanced states of development (Figures 20 and 21).

4 Mission Analysis and System Design

The BepiColombo spacecraft design is based on three scientific modules and two propulsion systems. The concept is thoroughly modular, so as to meet the environmental and mission requirements, minimize the complexity of the scientific modules, and take advantage of the most recent technology developments. The scientific modules, the Mercury Planetary Orbiter (MPO), the Mercury Magnetospheric Orbiter (MMO) and the Mercury Surface Element (MSE) are depicted in Figures 13, 16 and 19, respectively. The propulsion systems, the Solar Electrical Propulsion Module (SEPM) and the Chemical Propulsion Module (CPM), are identical for the two composites of the split launch, in order to minimize the procurement cost.

4.1 Mission Analysis

The mission requires the delivery of a mass of about 1100 kg at Mercury. The study has demonstrated the existence of a variety of options compatible with the mission requirements and programmatic constraints. The scenarios that have been analysed in detail are:

- a single launch (Ariane-5) with chemical propulsion only, or with a mixed chemical and solar electric propulsion (SEP) system;
- split launch of MPO and MMO-MSE (Soyuz-Fregat) with chemical and solar electric propulsions (with or without lunar swingby).

Both the chemical and mixed propulsion options use Venus gravity assists; the launch windows are spaced at intervals of 1.6 years. A split launch of MPO and MMO-MSE can take place either in the same window or in successive windows. Launches in May 2007 and January 2009 (or about half a year later, with a lunar swingby) have been considered. A significant drawback of the purely chemical option is the long cruise time (6 years or more) compared to that of the SEP option (2.1 to 2.5 years without lunar swingby, 3.5 years with lunar swingby). The combination of SEP with gravity assists provides opportunities with short cruise times and outstanding flexibility. The mass margin is larger with Ariane-5 and SEP, and adequate in all other options. Considerations of cost and schedule have resulted in the selection of a split launch with SEP in 2009 as the BepiColombo baseline.

In order to increase the mass margin, both spacecraft are launched into a high-apogee orbit, and reach their nominal escape velocity after a lunar swingby. In this way, the capability of the Soyuz-Fregat launcher provides a mass margin of the order of 20%, at the cost of a one-year longer transit time to Mercury. The Soyuz-Fregat performance considered is that expected for Mars Express in 2003, namely a 60-70 kg improvement with respect to the performance announced by Starsem for the end of 2001. Such an increase would correspond to the availability of a larger drop zone around

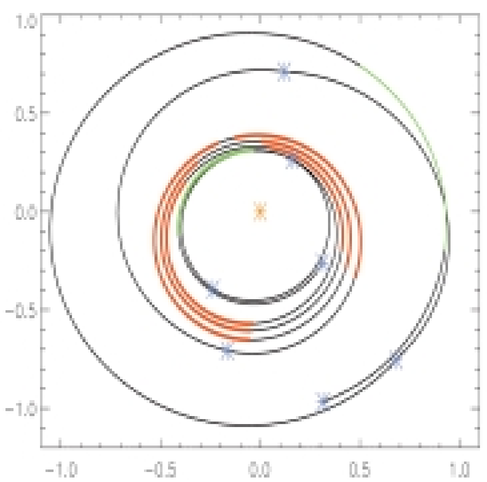
Table 12: Baseline mission parameters with Soyuz-Fregat.

Launch window	August 2009 (Lunar swingby)
Launch vehicle	Soyuz/Fregat
Initial orbit semi-major axis	320 000 km
Launch mass margin	23% (MPO) 19% (MMO-MSE)
SEP delta V	7.24 km/s
Thrust time (0.17 N)	1390 h
Thrust time (0.34 N)	6730 h
Cruise time	3.30 y
Mercury approach velocity	365 m/s

Baikonur, in Kazakhstan. A Soyuz ST+ version with a new third stage engine may be operational as early as 2002, providing an additional increase of 150-200 kg on top of the end-2001 launch performance.

Table 12 summarises the main parameters of the split-launch option with lunar swingby and SEP. Figure 22 shows the trajectory for a launch in August 2009 and an arrival at Mercury in October 2012.

The DS1 mission of NASA has successfully tested SEP in space on a modest scale. ESA's SMART-1, to be launched in late 2002-early 2003, will validate all system aspects of a mission associating SEP with gravity assists. The specific impulse of ion thrusters used for this study (3 400 s) is a realistic average



2007, 2.35 km/s, 9 deg N (Kourou), 8.36 km/s (700 kg), 8100 h

Figure 22: Ecliptic projection of Earth to Mercury trajectory for the August 2009 opportunity with lunar swingby. A first thrust arc increases the velocity relative to Earth from 1.4 to 2.8 km/s. After the Earth swingby, two Venus gravity assists (with a 180° transfer from Venus to Venus) and two Mercury gravity assists take place before final encounter with Mercury (red arcs: backward thrust, green arc: forward thrust).

between the beginning-of-life (BOL) and the end-of-life (EOL) values. The thrust times (<7000 h) are compatible with the demonstrated lifetime (10 000 h), and there are recovery strategies for single and some double thruster failures.

Capture and manoeuvres in the environment of Mercury would expose the SEPM solar array to the large infrared flux of the planet in addition to the direct solar illumination. This approach would require a complex strategy (several months long) to keep the array temperature within a tolerable envelope. Therefore, the entire SEPM is jettisoned at Mercury, and the capture and insertion manoeuvres are performed with the much more efficient 4 kN bi-propellant engine of CPM. This propulsion module also provides for a recovery in the case of a total failure of SEPM towards the end of the interplanetary cruise.

The two spacecraft composites are first inserted into the nominal MMO orbit (400 x 11 800 km, polar). In the case of MPO, another burn of the 4 kN engine lowers the apocentre to 1500 km, as required, and CPM is jettisoned after the completion of the second manoeuvre. For the MMO-MSE composite, MMO is first released in its orbit and MSE is then delivered to the surface by CPM at a latitude of 85°, for a nominal lifetime of at least 1 week.

The arrival conditions are such that both the MPO and MMO operational orbits have their line of apsides on Mercury's equator and their periherm on the anti-solar side at perihelion, in order to optimize the thermal environment (Figure 23).The orbits are resonant (four MPO revolutions last as long as one MMO revolution), so that communication between the orbiters is possible at periapsis, should one of the two high-gain antenna systems fail to perform according to specifications. The design lifetime of MMO and MPO is 1 Earth year (4 Mercury years or 2 Mercury solar days) in orbit around Mercury.

4.2 System Configuration

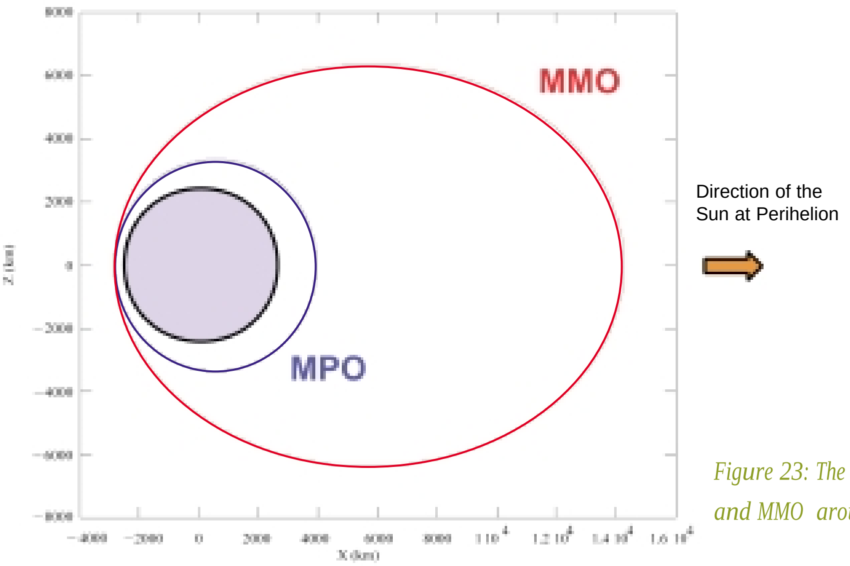


Figure 23: The orbits of MPO and MMO around Mercury.

Split-launch spacecraft configuration In the baseline scenario, the SEPM-CPM-MPO and SEPM-CPM-MMO-MSE composites are transported by two Soyuz-Fregats. SEPM consists of three 200 mN ion thrusters and two wings of GaAs solar cells (with 20% of optical solar reflectors) delivering a power of 5.5 kW at 1 AU. CPM features one 4 kN bi-propellant thruster (specific impulse = 315 s) and eight 20 N thrusters for attitude control. Through the interplanetary and early Mercury orbit phases, the command and control tasks are centralised in MPO and MMO.

Figures 24 and 26 show the launch configurations of the two composites; Figures 25 and 27 illustrate the respective flight configurations. Table 13 shows the mass budgets for launches in 2009 from Baikonur.

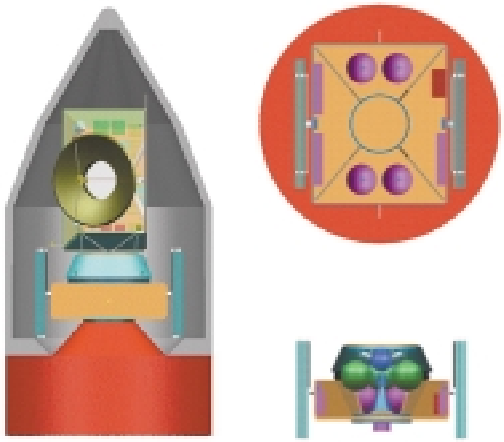


Figure 24: MPO launch configuration under the Soyuz fairing.

Single-launch spacecraft configuration In the single-launch scenario, which was not retained as a baseline because of its higher cost, all the modules are transported by a dedicated Ariane-5 (Figures 28 and 29). In this option, SEPM can accommodate

Table 13: Split-launch mass budget summary (kg).

Launch	MPO	MMO-MSE
Magnetospheric Orbiter	0.0	165.3
Surface Element	0.0	44.1
Planetary Orbiter	357.3	0.0
Chemical Propulsion Module (dry)	71.1	71.1
Subtotal 1 (dry mass at Mercury)	**428.4**	**280.5**
Bi-propellant	155.9	333.6
Subtotal 2 (mass after jettison)	**584.3**	**614.1**
SEPM (dry)	365.5	365.5
Subtotal 3 (mass before jettison)	**949.8**	**979.6**
Cruise propellant	230.3	237.5
Launch vehicle adapter	49.0	49.0
Launch mass	1229.0	1266.1
Soyuz-Fregat limit launch mass	1509.6	1509.6
System margin	**280.6 (23 %)**	**243.5 (19 %)**

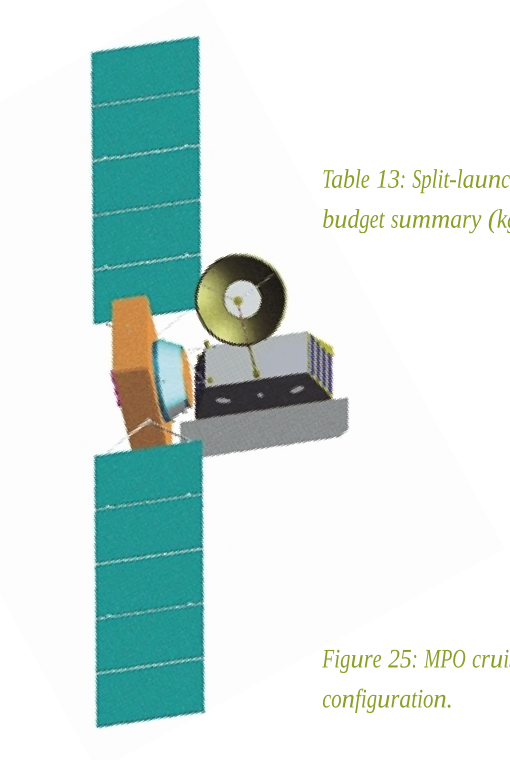


Figure 25: MPO cruise configuration.

Figure 26: MMO-MSE configuration under the Soyuz fairing.

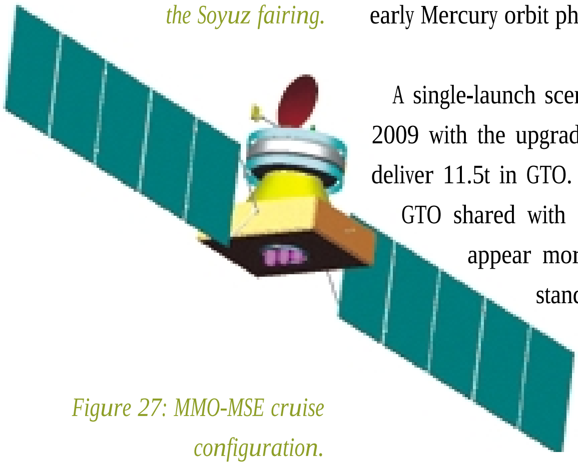


Figure 27: MMO-MSE cruise configuration.

Figure 28:(far right) Single-composite launch configuration.

Figure 29: Single-composite cruise configuration.

either gridded-ion or stationary plasma thrusters, resulting in launch masses of 2602 kg or 2942 kg (versus an Ariane-5 launch capability of 3500 kg into the required escape orbit, with a 2.8 km/s hyperbolic excess velocity) and mass margins of 35 % and 19 %, respectively. This flexibility is advantageous from the point of view of thruster procurement. The main differences lie in the required propellant mass and electrical power (6.5 kW for the stationary plasma thrusters and 10.5 kW for the ion thrusters). The command, control and telecommunication tasks are centralised in MPO through the interplanetary and early Mercury orbit phase.

A single-launch scenario may also be feasible by 2009 with the upgraded Ariane-5 E/CB which will deliver 11.5t in GTO. A launch of BepiColombo in GTO shared with another passenger may then appear more attractive from a financial standpoint, but no cost model is available yet and this option has not been analysed further. Other questions relate to the possible re-starting of the cryogenic upper stage after a long coast arc, the flexibility of the launch hour (normally around midnight for commercial satellites bound for geostationary orbits) and the duration of the launch window (normally several months for a launch shared with a commercial passenger).

It has been verified that the dual spacecraft configuration is also compatible with the present Ariane-5, using the Speltra adapter. This option is more expensive, but may be considered as a back-up if, for example, the Soyuz-Fregat launcher were no longer available towards the end of this decade. The launch window is the same as for the single-composite Ariane-5 scenario, and the mass margin remains >30 %.

4.3 System Elements

Solar Electric Propulsion Module Electric propulsion is optimal for slow cruise manoeuvres, but unsuitable for quick insertion needs. Moreover, the large cruise arrays can hardly withstand the near-Mercury thermal environment without major developments. Solar arrays derived from a standard design developed for communication satellites (with a maximum operational temperature of 150 °C), and optimised for extreme thermal conditions, have been adopted. The available electrical power and the temperature of the array increase as the spacecraft approaches the Sun. Once the temperature has risen to 150 °C, the array is progressively tilted away from the Sun direction, by up to 65°. In this way, the power remains approximately constant, from 0.6 to 0.32 AU, at a level twice that available at 1 AU.

SEPM may be regarded as the prototype of an upper stage for a wide range of Solar System exploration missions requiring a high post-launch velocity increment.

Due to the relatively limited launch capability of Soyuz-Fregat, ion thrusters are the sole candidates for SEPM. Two thrusters with similar characteristics, the radio-frequency ion thruster (RITA-XT) and electron bombardment thruster (T6 IPS), have been considered (Table 14, below).

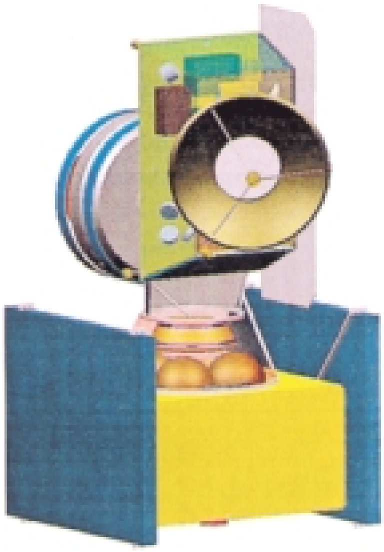


Table 14: Ion thruster characteristics

Thrust level (per unit)	150-200 mN
Dry mass (3 units)	85 kg
Beam voltage	1300 V
Specific impulse, BOL/EOL	3500 s / 3200 s
Power @ 170 mN (per unit)	5 kW

SEPM is a simple rectangular prism. The main structural element is a central thrust cone which houses the Xe propellant tanks and transmits the loads to the launcher interface. Two wings, consisting of several panels equipped with GaAs cells, provide the power required during the cruise; they are mounted on drive mechanisms to enable their orientation to be modified during the cruise. Table 15 summarises the main characteristics of this module.

Number of thrusters	3 (1 or 2 in operation)
Nominal thrust level	0.17 or 0.34 N
Array power @ 1 AU	5.5 kW
Array size	33 m^2
Dry mass	365 kg
Wet mass	596 kg (MPO), 604 kg (MMO-MSE)

Chemical Propulsion Module CPM hosts the bi-propellant propulsion system employed for attitude control during the cruise, Mercury orbit insertion, and MSE de-orbiting and descent. The attitude control functions are performed with a redundant set of eight 20 N thrusters, while the other manoeuvres are achieved with a 4000 N engine. Alternative engines with lower thrust (down to 1500N) may also be used, depending on their availability. CPM also serves as a structural interface between SEPM and the scientific modules, and carries attitude and orbit control system (AOCS) sensors and the CLAM-D camera head (MMO-MSE mission). The CPM structure consists essentially of a main platform, which supports the elements of the propulsion system, and of a short interface cone, which caps the SEPM thrust cone and provides a mounting interface for MMO and MPO. The propellant tanks protrude under the platform into SEPM to minimise the total height of the system. The lower side of CPM is insulated to provide thermal protection after the jettisoning of SEPM.

MPO is mounted on CPM in such a way that it maintains the same attitude with respect to the Sun and planet as during the operational phase (Figure 30). In the MMO-MSE mission, MMO remains momentarily attached to the interface cone after separating from the CPM-MSE composite, as shown in Figure 31. The interface cone is jettisoned afterwards. MSE is supported by brackets which are welded to the propulsion tanks. Table 16 gives the main CPM design parameters.

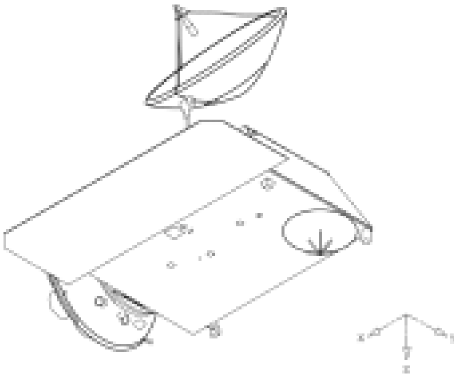


Figure 30: CPM-MPO composite configuration after jettison of SEPM.

Number of thrusters	1 + 8
Maximum thrust	4,000 N / 20 N
Dry mass*	71.1 kg
Wet mass	227 kg (MPO) 405 kg (MMO-MSE)

*including 18.8 kg for the interface cone

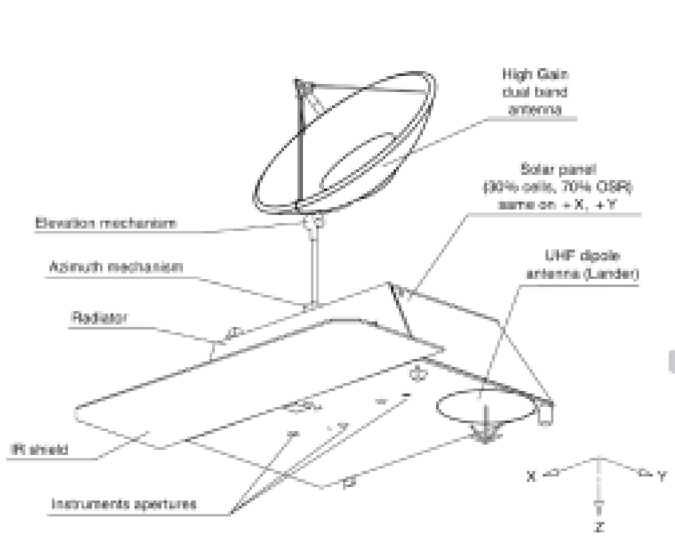
Table 15 (left): SEPM design parameters.

Table 16 (right): CPM design parameters.

Planetary Orbiter The configuration of the planetary orbiter is largely driven by thermal constraints (Figure 32). The spacecraft is protected from the Sun and Mercury radiations by high-efficiency insulation and the internal heat is rejected by a large radiator. The body is a flat prism with three sides slanted at 20° (±X, +Y) which form a solar array capable of delivering 420 W at perihelion; the surface of the array is covered by solar cells (30 %) and optical solar reflectors (70 %) mounted on an Al substrate.

The radiator is located on the -Y side and has an area of 1.5 m^2, large enough to dissipate a power of up to 200 W. The nominal attitude of the spacecraft is such that the radiator is never illuminated by the Sun (Figure 33); the +Z axis is always aligned with the nadir direction and the spacecraft is rotated by 180° around this axis every half Mercury year. The radiator is protected from the planet infrared flux by a shield which must have an area of 3.4 m^2 for a minimum altitude of 400 km; the shield is stowed against the radiator at launch.

Figure 31: CPM-MSE composite after separation from MMO and interface cone.



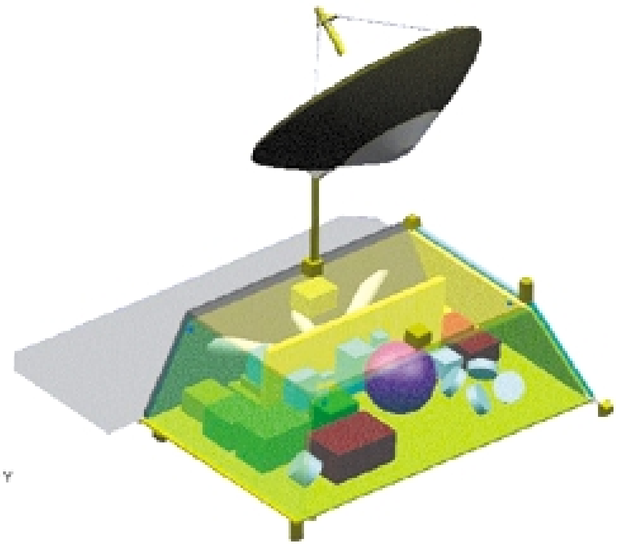
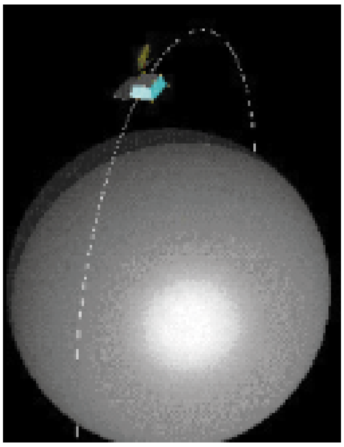


Figure 32: MPO Configuration

Figure 33: MPO operational attitude.



Three star sensors and the telescope which view the sky through apertures in the radiator, and the high-resolution camera which views the surface with a dichroic mirror, are mounted on a thermally and mechanically stable bench-like structure. The entire spacecraft body, with the exception of the radiator and remote sensing instrument apertures, is protected by high-temperature multi-layer insulation.

The major external element of the telemetry, tracking and command (TT&C) subsystem is a deployable, 1.5 m diameter high-gain antenna (HGA), mounted on a short boom on the zenith side; it can be pointed in azimuth and elevation and is restrained at launch by a latch mechanism. The scientific data are transmitted to Earth in Ka-band, in a suppressed-carrier mode, at a rate which is a function of the distance to Earth, during about 25% of the time (assuming one ground station and taking into account the time lost during planet occultations). The overall data return is 1550 Gb in 1 year. A ultra-high-frequency (UHF) dipole array, mounted on the nadir side, is used for possible communications with MSE. Table 17 gives the MPO mass budget.

Table 17: MPO mass budget.

Subsystem	Mass (kg)
Structure & Mechanisms	88.7
Thermal Control	47.1
RCS including Propellant	24.7
Power & Harness	48.6
Solar generator	5.6
AOCS	23.6
Data Handling	26.0
TT&C (X/Ka-band)	33.0
Payload	60.0
Total	**357.3**

Magnetospheric Orbiter MMO has the shape of a flat cylinder and spins at 15 rpm around an axis perpendicular to the equator of Mercury (Figure 34). The top and bottom surfaces act as radiators; an active temperature control is implemented with louvres in order to maintain an acceptable temperature for the equipment and cope with the wide excursion of the environmental conditions. The side wall is protected by thermal blankets and is covered with second-surface mirrors and solar cells, forming an array which delivers a power of 185 W.

The cold gas tank for the reaction control system (RCS) is located near the centre of mass inside a truncated cone made of carbon-fibre-reinforced plastics. The equipment is mounted on an inner cylindrical wall and on two platforms which are attached with flanges to the main conical element.

The communications with Earth are achieved with a despun high-gain offset antenna (HGA) and two medium gain antennas (MGAs) operating in X-band. The HGA is used as the main link with the Earth, in orbit around Mercury; this task is accomplished with the MGAs during the cruise. Due to the orbital inclination of Mercury, the HGA must have the ability to point within $\pm 12^{0}$ in elevation. The telemetry will return 160 Gb of data in 1 year (residual-carrier mode, 20 W RF transmitter power). The communication with the Mercury lander is achieved with a microstrip UHF patch antenna located on the opposite side. Table 18 gives the MMO mass budget

The deployable booms and attached sensors are stowed during the launch and cruise phases, they are fixed on both sides of the structural cone to specially reinforced supports and hold-downs.

Surface Element MSE performs measurements on the surface of Mercury for at least one week. The lander is aimed at a latitude of 85° in the terminator region where the mean surface temperature lies in the range –50 to +65 °C. The 0.9 m diameter MSE has a mass of 44 kg, including 7 kg of payload.

Following the release of MMO, a burn of the 4 kN CPM thruster inserts MSE on a low-periherm (10 km) orbit. At the end of a 75-minute autonomous descent, a final braking manoeuvre is performed from an altitude of about 10 km until zero velocity is reached at a height of approximately 120 m above the surface. This manoeuvre is controlled with gyros/accelerometers and an optical range/range-rate sensor. MSE then separates from CPM which crashes at a distance larger than 100 m from MSE, in order to prevent chemical contamination of the landing site. Airbags are preferred to crushable material as an impact attenuator, because the latter is more sensitive to the nature of the terrain. A maximum touchdown speed of 30 m/s is attained after a 120 m free fall. This terminal velocity is comparable with that achieved with a parachute landing system under development for Mars. Using the same airbag design, a similar impact deceleration of 250 g will be experienced for 38 ms in both cases. A whole range of ruggedised equipment (payload instruments, power system, avionics) to be used on Mars landers will therefore be available for MSE. The complete deployment sequence of the MMO-MSE composite is depicted in Figure 35.

The MSE design is driven by severe mass constraints, and by the risk inherent in a landing in a largely uncharted and possibly shadowed area; 40 % of the terrain is estimated to be in shadow at a latitude of 85°. The lander concept therefore relies on a primary battery with high energy density (1.7 kWh capacity). Operations can therefore be carried out even in a completely shadowed area for about one week. An optional small solar generator (about 0.5 kg) could nevertheless feed the load, or part of it, directly without a secondary battery, thus allowing extended surface operations.

No mechanisms are used in MSE, except for the deployment of individual payload components (tethered micro-rover and mole), therefore increasing the system reliability. The craft is fully insulated to cope with the low-temperature environment in a shadowed area. Should the landing occur in sunlight, a jettisonable cover would be expelled to enable a topside radiator to dump waste heat from MSE. The radiator is slightly recessed inside the MSE structure and is protected from the Sun for elevations of up to 20°.

Communications, data handling and power supply subsystems will consume about 1.4 kWh, leaving 300 Wh of primary energy for the payload. The scientific data are stored in a mass memory; either MPO or MMO can be used as a relay at each overhead pass. The MSE to MMO UHF link provides for a mean usable data rate of 8.7 kb/s, corresponding to a total of 75 Mb for 7 days of operation (18 contact periods of 480 s). For instance, 68 Mb may be used for imagery (compressed), namely high-resolution and colour

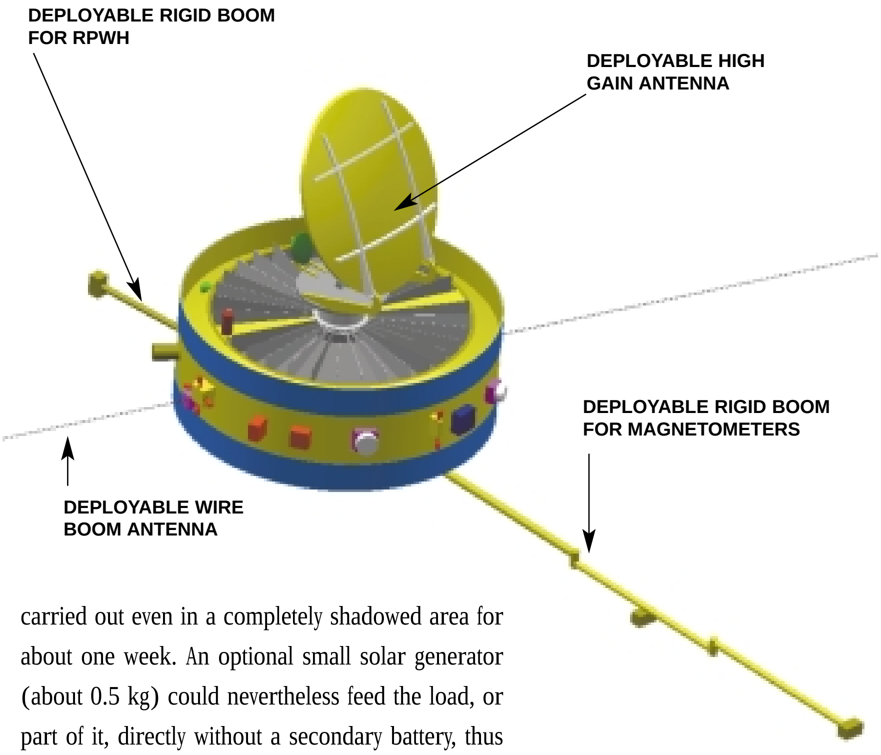


Figure 34: MMO configuration.

Table 18: MMO mass budget.

Subsystem	Mass (kg)
Structure	32.0
Thermal Control	15.5
AOCS + RCS and propellant	12.0
Power	15.8
Harness	18.5
Data Handling	5.5
TT&C (X-band)	28.7
TT&C (UHF)	3.5
Rigid boom assembly for MAG	5.0
Rigid boom assembly for RPW-H	2.0
Positive ion emitter	2.7
Payload	24.1
Total	**165.3**

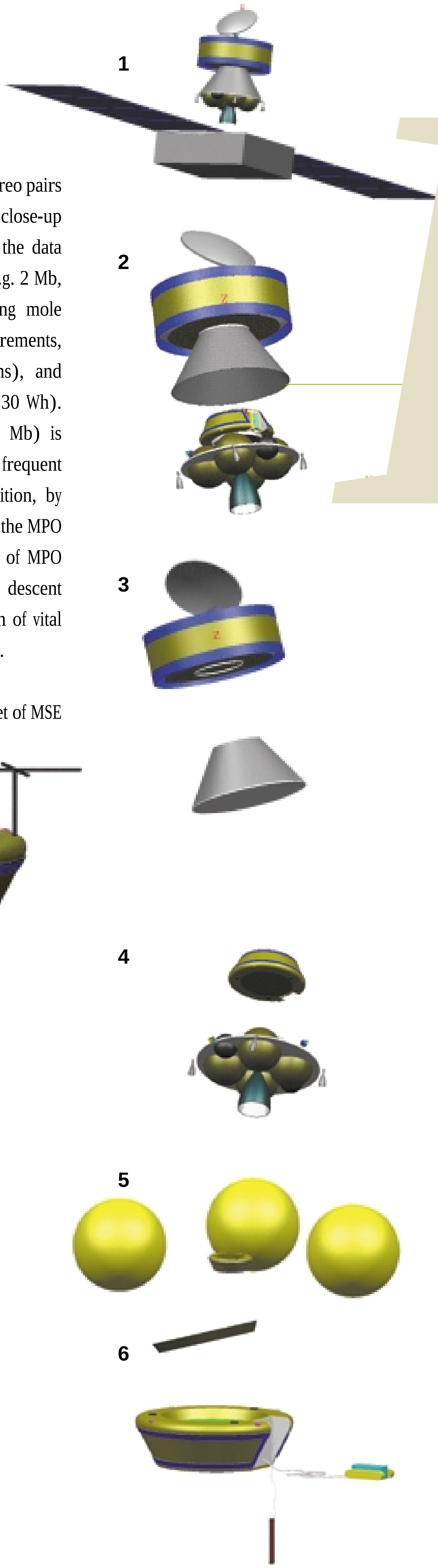


Figure 35: Deployment sequence of the MMO-MSE spacecraft composite (from top to bottom): (1) SEPM jettison, (2) separation of MMO from CPM-MSE, (3) jettison of the interface cone from MMO, (4) separation of MSE from CPM, (5) MSE landing and airbag separation, (6) MSE on the ground with deployed payload and thermal protection cover jettisoned.

images taken by CLAM-D during descent, stereo pairs of the surface from CLAM-S, and possible close-up images from the micro-rover. The rest of the data volume and energy is shared among HP^3 (e.g. 2 Mb, 73 h of measurements, 120 Wh including mole operation), AXS (2 Mb, 6 h of measurements, 150 Wh including micro-rover operations), and MLMAG (3 Mbit, 100 h of measurements, 30 Wh). Nearly twice this total data volume (138 Mb) is provided by the MSE to MPO link (more frequent contacts due to the lower orbit). In addition, by appropriately phasing the MSE descent with the MPO orbit, it is possible to ensure the visibility of MPO from MSE for at least a portion of the descent trajectory, so that the low rate transmission of vital parameters can be maintained until landing.

The overall configuration and mass budget of MSE are shown in Figure 36 and Table 19.

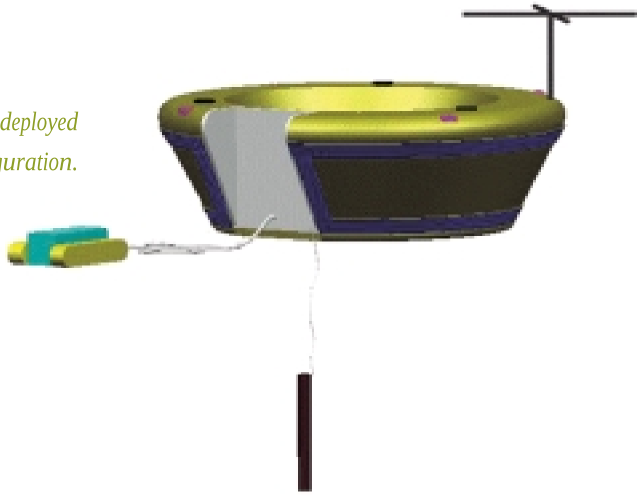


Figure 36: MSE deployed configuration.

Table 19: MSE mass budget.

Subsystem	Mass (kg)
Structure	15.3
Mechanisms	1.2
Thermal Control	3.2
AOCS	0.6
Data Handling	1.4
TT&C (UHF Relay)	2.5
Power	11.2
Harness	1.4
Payload	7.2
Total	**44.1**

5 Operations

5.1 Science Operations

The BepiColombo science operations concept draws on the experience gained with Rosetta, Mars Express, and SMART-1. Activities will include preparation of a long-term plan (Science Master Plan), a short-term payload operation plan, and guidelines for science data archiving. A Science Operations Team will conduct the operations under the responsibility of the ESA Project Scientist. The team will be located at a dedicated Scientific Operations Centre during critical phases of the mission.

5.2 Ground Segment and Spacecraft Operations

ESOC will conduct the mission operations of all elements of the BepiColombo mission. Spacecraft operations will include mission planning, spacecraft monitoring and control, and orbit and attitude determination and control. The mission planning concept will follow the methods of interplanetary mission operations developed for Rosetta, Mars Express, and SMART-1. In particular, the electric propulsion cruise operations concept will be derived from experience gained from SMART-1, while in-orbit operations will resemble in many aspects those of Mars Express.

The ground segment will include the ground stations and the communications network, the Mission Operations Centre located at ESOC, the flight control system, the spacecraft simulators, and the data disposition system. The ground stations used for BepiColombo will be the 35 m ESA Perth station (X/Ka-band) during all mission phases, the 15 m ESA Kourou station during the launch and early orbit phase and critical phases, and the 15 m Villafranca station as a back-up.

6 Management

6.1 Science Management and Instrument Selection

A BepiColombo Science Management Plan will be submitted for approval to ESA's Science Programme Committee.

A BepiColombo Science Working Team, comprising the Principal Investigators and the Interdisciplinary Scientists, and chaired by the ESA Project Scientist, will be established to support the project and to maximise the scientific return of the mission.

6.2 Development Philosophy and Schedule

The BepiColombo development philosophy is based on a structural and thermal model and an electrical qualification model to be built for the development and qualification of the mechanical and electrical subsystems. The protoflight model of the spacecraft will be the only model up to flight standard. Spare units will be procured for off-the-shelf equipment, and repair kits for purpose-built equipment.

The development philosophy will follow the procedures currently being applied in the Mars Express mission, with the payload interfaces managed directly by the industrial contractor.

The BepiColombo master schedule for the baseline 2009 split-launch is shown in Figure 37. A start of Phase-B in early 2003 allows a 6-month contingency period to be maintained.

A technology development phase precedes the start of Phase-C/D in 2004. The key technologies to be developed for BepiColombo include:

- Thermal control for high temperatures (thermal control materials, heat pipes embedded into structural panels, louvres)
- Solar generators for high intensities, high temperatures (GaAs cells and cell module assemblies, arrays and array drive mechanisms)
- Antenna technologies for high temperatures (reflector materials, feed and pointing/despin mechanisms)
- Avionics/guidance, navigation and control (highly integrated control & data systems, vision-based range/range-rate system for landing).

The high-temperature-related technologies are of broad applicability to missions in the inner Solar System, while the avionics/guidance, navigation and control-related technologies are applicable to a wide range of planetary missions with miniaturised orbiters and landers.

6.3 International Co-operation

Space agencies other than ESA are considering missions to Mercury.

NASA has recently selected the Messenger Orbiter mission in the framework of the Discovery programme. Representatives of the Messenger and BepiColombo teams have met and stated the similarities of their objectives. They have recognized the significantly greater scientific breadth of the larger and more ambitious ESA Cornerstone. Several specific areas of possible coordination between the two missions have been identified, including simultaneous magnetospheric measurements, identification of landing sites, complementary measurements of surface features from different phase angles, co-operative use of ground stations, and extension of the temporal baseline for fundamental-physics measurements.

Discussions with Japanese scientists and ISAS management have also taken place, and have highlighted the strong Japanese interest in the exploration of Mercury, as was evident in the earlier inclusion of a mission to this planet in the ISAS medium-term planning. However, this mission was removed from the plan because of programmatic constraints. As a result there is a growing Japanese interest in participating in BepiColombo.

The main opportunity being considered is that ISAS might contribute the Mercury Magnetospheric Orbiter (MMO). In this scenario, ESA would be responsible for system-level MMO interfaces, and for its integration with SEPM, CPM, and MSE. ISAS would also contribute elements of the ground segment (MMO Mission Operations Centre and 64 m Usuda station). Exchange of hardware is also conceivable, e.g. development in Europe of the high-temperature antenna reflector and despin mechanism for MMO (synergy with the MPO antenna), and procurement in Japan of off-the-shelf 1.7 kN MON/hydrazine engines (used for ETS-VI, COMETS) for the two CPMs. Budgetary approval at ministerial level for such an initiative would be granted to ISAS in early 2002.

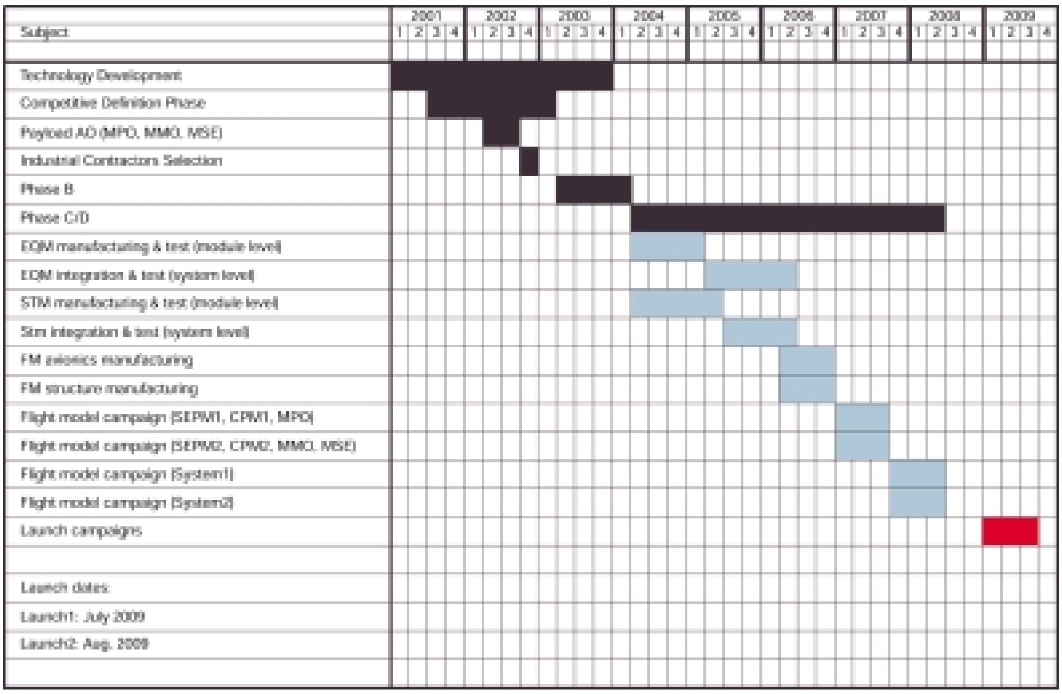


Figure 37: Master schedule.

7 Conclusion

- BepiColombo offers the European Space Agency the chance to make a remarkable new contribution to our knowledge of the Solar System, by venturing into the hot region near the Sun and exploring Mercury, the most enigmatic of the Earth's sisters among the terrestrial planets.

- Deeper understanding of the Earth itself, and the emergence of its life-giving qualities, requires a much better grasp of the tumultuous circumstances of its birth. Mercury promises to provide a unique perspective on the origin of planets close to the Sun - and, by inference, near other stars too.

- The magnetism of planets and their interactions with the solar wind provide another major theme in space science, again with great relevance to the Earth. Here too the small planet Mercury, with its surprising magnetic field and its proximity to the Sun, has a distinctive tale to tell.

- Compared with planetary science in NASA, ESA's is embryonic, despite the success of Giotto and the high hopes for Huygens, Mars Express and Rosetta. As a bold planetary mission, BepiColombo will consolidate this important branch of European space science.

- The strong gravitational field of the Sun, felt by the orbit of Mercury, provided Einstein with a natural laboratory for proving Newton wrong. Operating on the scene, and with far higher precision, BepiColombo can now look for possible violations of Einstein's own theory of general relativity.

- Another big bonus from BepiColombo will be an insider's view of the asteroids that pass close to the Earth and carry a long-term risk of impact. In particular, a new class of asteroids confined within the Earth's orbit will be easier to detect from Mercury than from the ground or near space.

- The scientific payloads required to fulfil these purposes rely on proven technologies that have, for the most part, already flown on earlier planetary missions. This does not rule out the development of improved instruments as the preparation of the mission proceeds.

- The BepiColombo mission is conceived with a low-cost approach. A split Soyuz launch can provide a fleet of three science elements within a moderate cost envelope. These self-contained elements also create opportunities for international co-operation with easily defined interfaces.

- The mission architecture provides numerous recovery options, for example by the use of the Chemical Propulsion Module in the case of degradation of the electrical propulsion, or by element-to-element data relay in the case of loss of direct-to-Earth communications on one of the Orbiters.

- The design of the Surface Element emphasises a safe landing and operation in uncharted terrain, and exploits hardware developed in Europe for Mars landers (Beagle 2, NetLander). Very few novel technologies are needed; they focus essentially on a highly re-usable vision-based navigation system.

- The Solar Electric Propulsion Module is a new vehicle, but it will exploit the state-of-the-art solar generator and electric propulsion hardware available from large tele-communications satellites. It will be the prototype of a low-cost upper stage for a medium launcher of the Soyuz class, for missions needing large post-launch velocity increments, including most future Solar System exploration.

- The BepiColombo technology R&D activities will focus on equipment able to operate in a high-temperature, high-solar-intensity environment, as well as on miniaturization of hardware. These technology lines will be enabling for future missions to the inner Solar System (Sun, Venus), and for mass-critical missions in general, including all future Solar System exploration.